Sensors & Actuators

Lecture 7

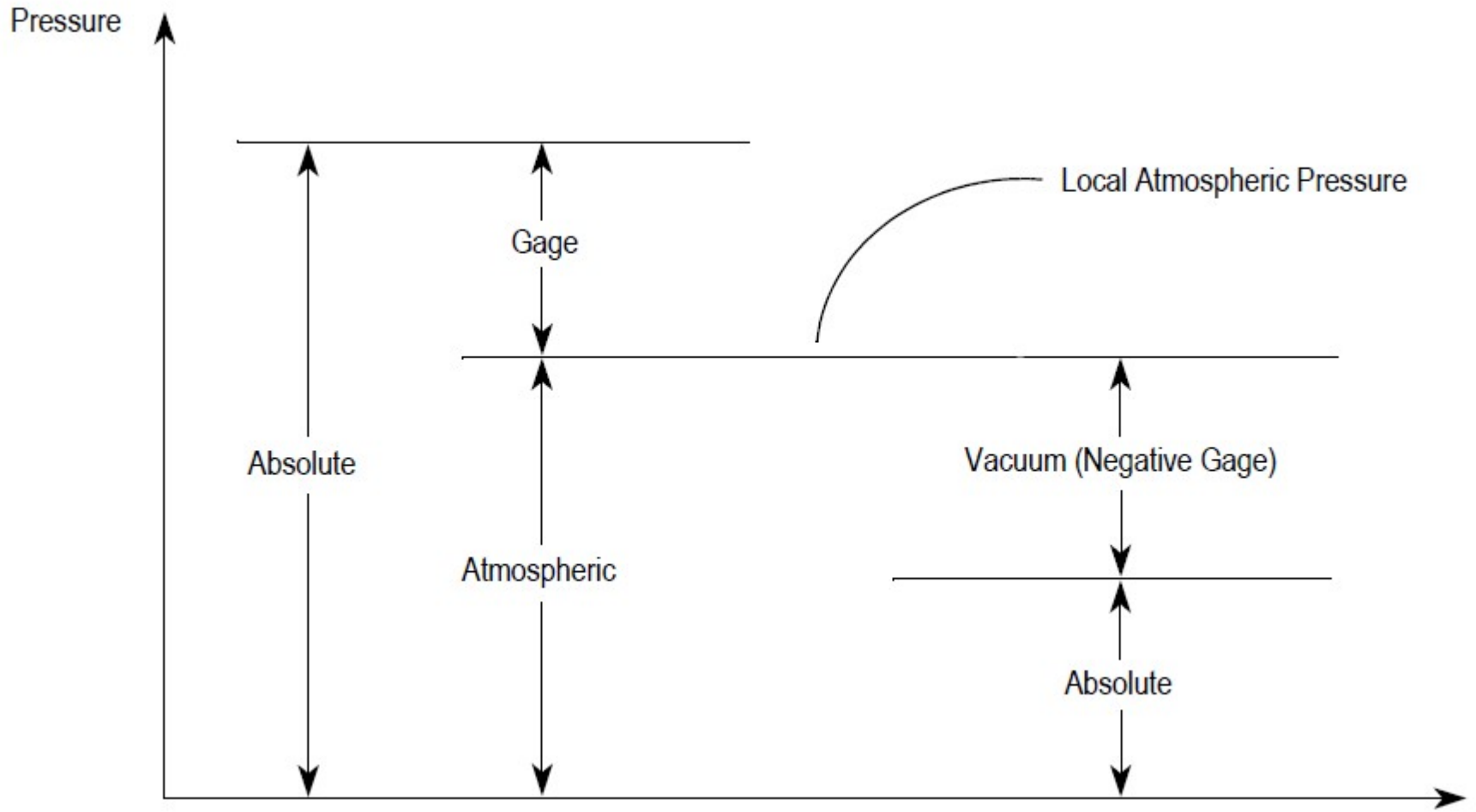
Sensing/ Measurement Process:

Standards, Documentation, Errors, & Calibration

Measurement Standards: Definitions

- *Measurement standards* are those devices, artifacts, procedures, instruments, systems, protocols, or processes that are used to define (or to realize) measurement units and on which all lower echelon (less accurate) measurements depend.
- Another definition of a standard is a unit of known quantity or dimension to which other measurement units can be compared.

Pressure Term Relationships



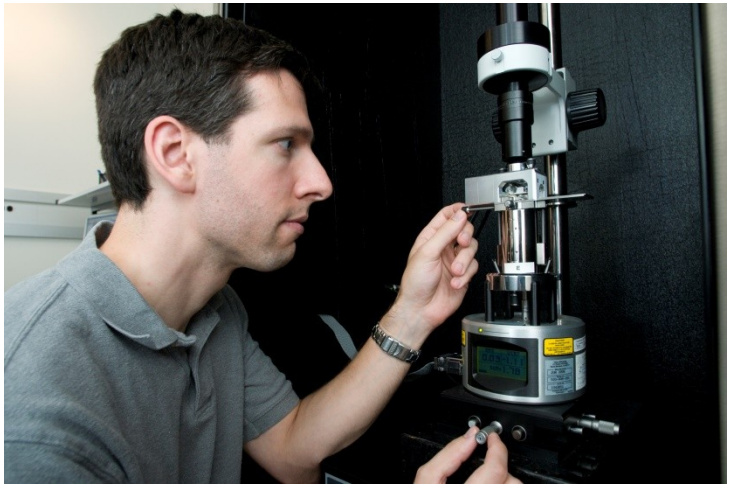
Conversion Table for Common Units of Pressure

	kPa	mm Hg	millibar	in H_2O	PSI
1 atm	101.325	760.000	1013.25	406.795	14.6960
1 kPa	1.000	7.50062	10.000	4.01475	0.145038
1 mm Hg	0.133322	1.000	1.33322	0.535257	0.0193368
1 millibar	0.1000	0.750062	1.000	0.401475	0.0145038
1 in H_2O	0.249081	1.86826	2.49081	1.000	0.0361
1 PSI	6.89473	51.7148	68.9473	27.6807	1.000
1 mm H_2O	0.009806	0.07355	9.8×10^{-8}	0.03937	0.0014223

Measurement Process

- A measurement process is a set of operations used to determine the value of a quantity (ISO 9000:2000, point 3.10.2)

http://www.iso.ch.



Measurement Standards

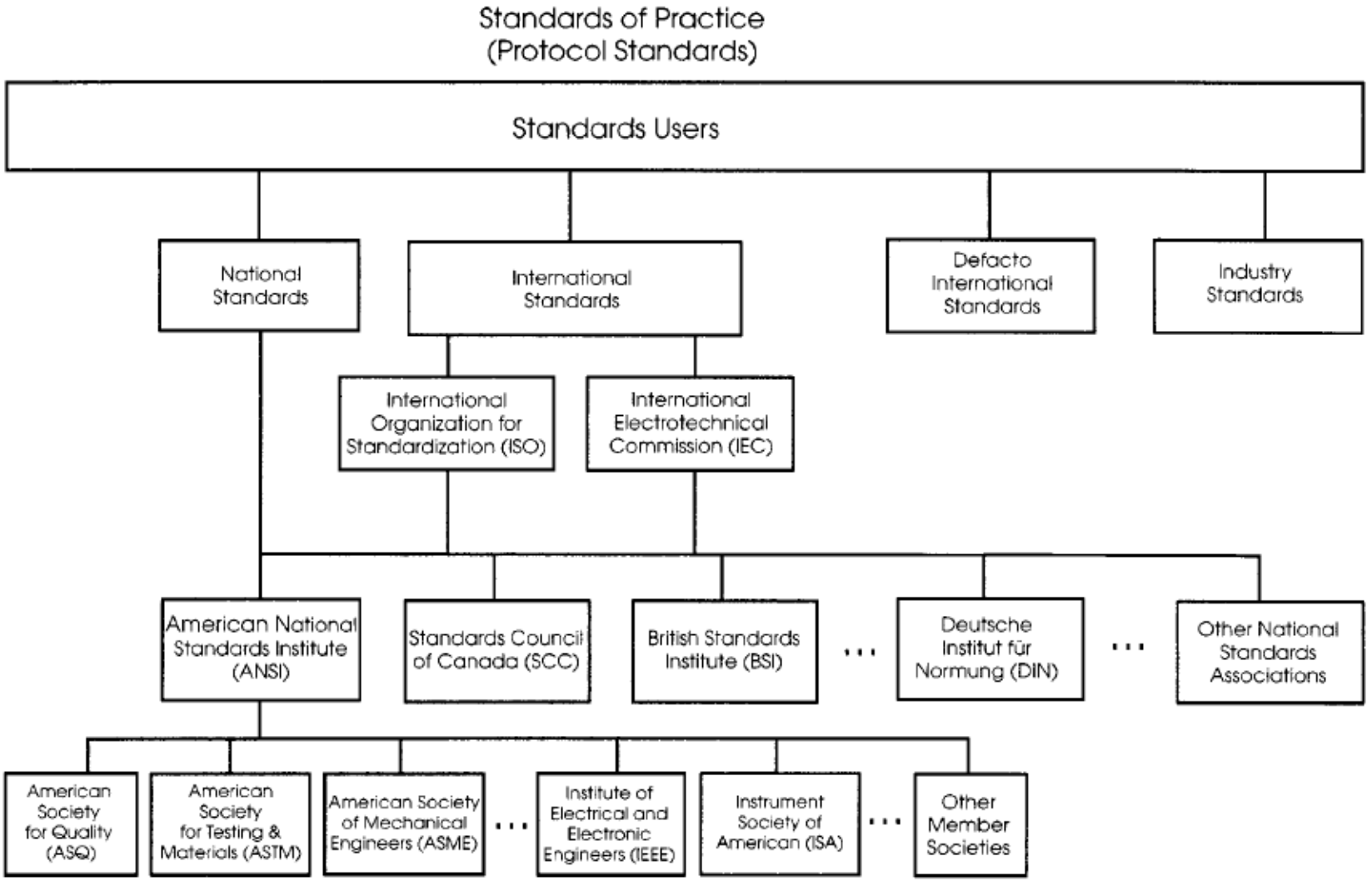
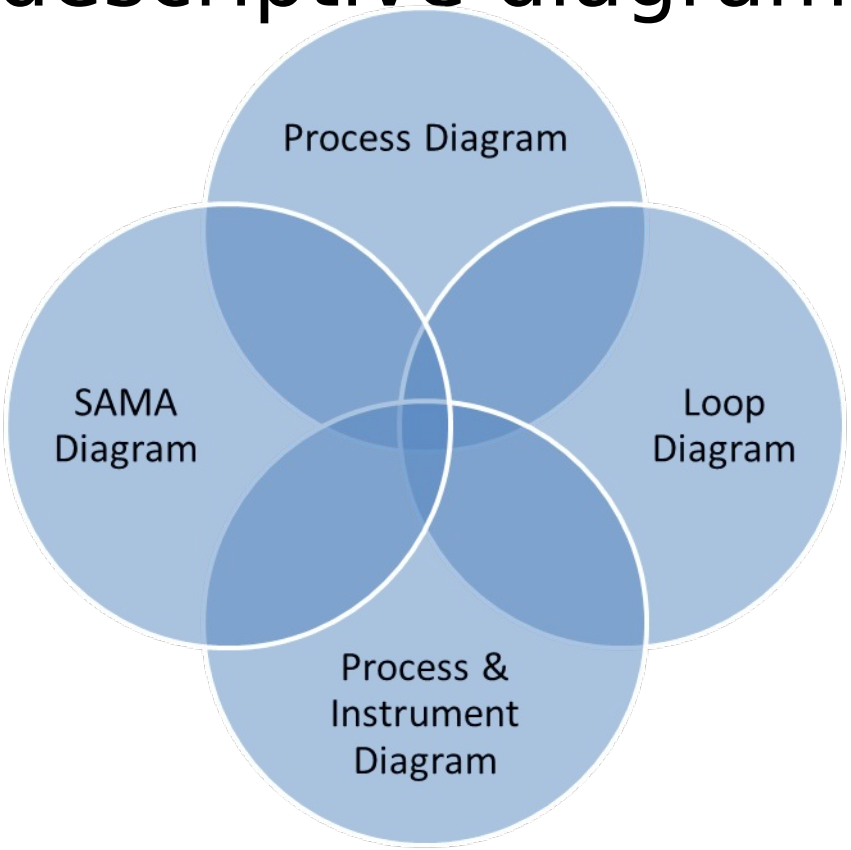

Standards of Practice
(Protocol Standards)
Standards Users
National Standards
International Standards
Defacto International Standards
Industry Standards
International Organization for Standardization (ISO)
International Electrotechnical Commission (IEC)
American National Standards Institute (ANSI)
Standards Council of Canada (SCC)
British Standards Institute (BSI)
Deutsche Institut für Normung (DIN)
Other National Standards Associations
American Society for Quality (ASQ)
American Society for Testing & Materials (ASTM)
American Society of Mechanical Engineers (ASME)
Institute of Electrical and Electronic Engineers (IEEE)
Instrument Society of American (ISA)
Other Member Societies

Table 1. Selected glossary of terms on error and uncertainty (http://www.rit.edu/~vwlsps/uncertainties/uncertaintiespart2.html#glossary).

Term	Brief definition
Absolute error	An error in a quantity, having the same units as the quantity. For $c = (2.95 \pm 0.07)\ \mathrm{m\,s^{-1}}$, the absolute error is $0.07\ \mathrm{m\,s^{-1}}$.
Accuracy	How close a measurement is to being correct. $g = 9.7\ \mathrm{m\,s^{-2}}$ on earth is more accurate than $g = 9.532706\ \mathrm{m\,s^{-2}}$. See *precision*.
Average	When several measurements of a quantity are made, the sum of the measurements divided by the number of measurements.
Average deviation	The average of the absolute value of the differences between each measurement and the average. See *standard deviation*.
Confidence level	The fraction of measurements that can be expected to lie within a given range.
Deviation	A measure of range of measurements from the average. Also called *error or uncertainty*.
Error	A measure of range of measurements from the average. Also called *deviation* or *uncertainty*.
Estimated uncertainty	An uncertainty estimated by the observer based on his or her knowledge of the experiment and the equipment.
Gaussian distribution	The familiar bell-shaped distribution, assumed for random errors. Also called *normal distribution*.
Independent variables	Changing the value of one variable has no effect on other variables. *Error propagation* assumes this independence.
Instrument limit of Error (ILE)	Smallest reading that an observer can make from an instrument. This is generally smaller than the *least count*.
Least count	Size of the smallest division on a scale. Typically the *ILE* equals the least count or 1/2 or 1/5 of the least count.
Precision	The number of significant figures in a measurement. $g = 9.532706\ \mathrm{m\,s^{-2}}$ is more precise than $g = 9.7\ \mathrm{m\,s^{-2}}$.
Propagation of errors	Method of determining an uncertainty in a function of independent variables each with their own uncertainty.
Random error	Deviations from the 'true value' can be equally likely to be higher or lower than the true value. See *systematic error*.
Relative error	The ratio of absolute error to the average, Dx/x. Also called percentage error or fractional uncertainty. See *absolute error*.
Standard deviation	The statistical measure of uncertainty. See *average deviation*.
Systematic error	A situation where all measurements fall above or below the 'true value'. To realize and correct systematic errors is difficult.
Uncertainty	A measure of range of measurements from the average. Also called *deviation* or *error*.

Instrumentation Documentation

- This is the standardized way of making descriptive diagrams

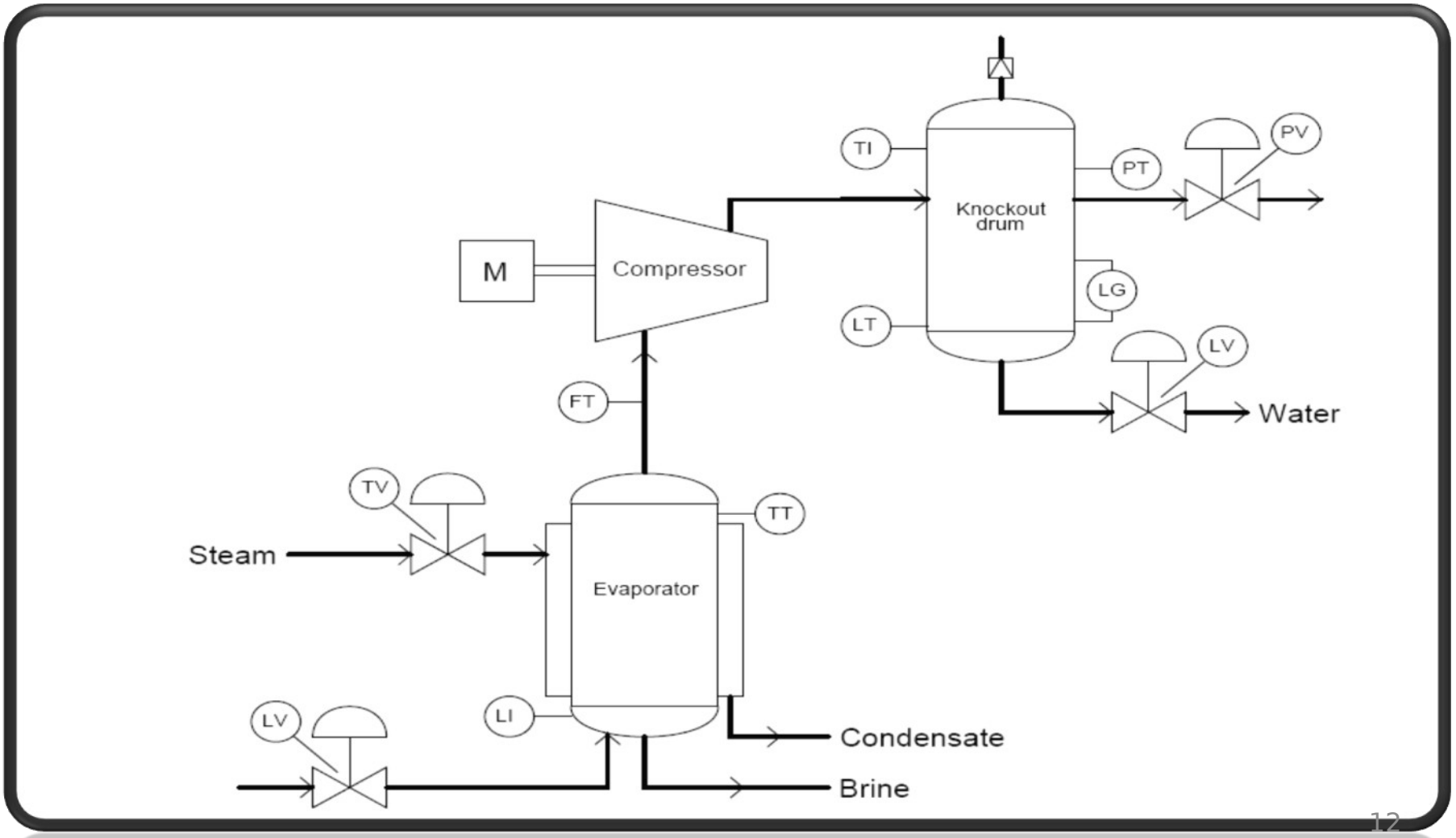


Types of Instrumentation Documentation

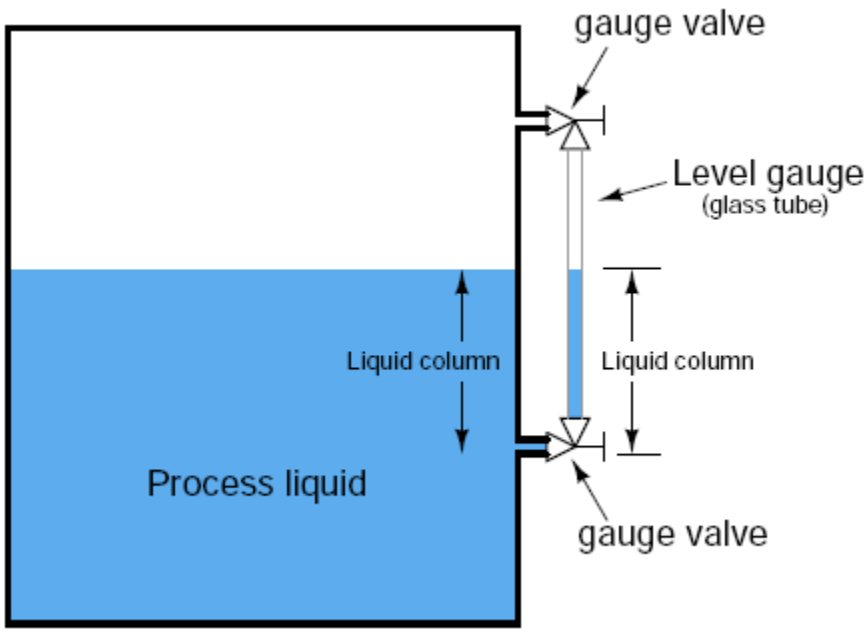
- At the highest level, we are interested in the interconnections of process vessels, pipes, and flow paths of process fluids.
- “Big picture” of a process is called a process flow diagram
- At the lowest level, we might be interested in the interconnections of individual instruments, including all the wire numbers, terminal numbers, cable types, instrument calibration ranges, etc.
- The proper form of diagram for this level of fine detail is called a loop diagram.
- Process and instrument diagrams (P&IDs) lie somewhere in the middle between process flow diagrams and loop diagrams.
- SAMA (Scientific Apparatus Makers Association) diagrams are used for an entirely different purpose: to document the strategy of a control system.
- In a SAMA diagram, emphasis is placed on the algorithms used to control a process,

Analogy of Diagrams with Globe, Atlas, City Map, Street Map

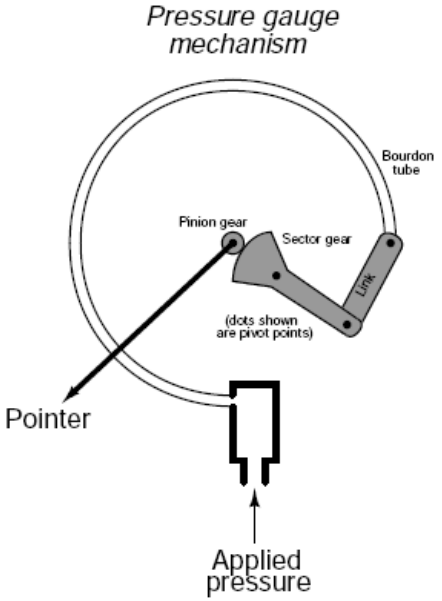
Process Flow Diagram



Level Gauge


gauge valve
Level gauge
(glass tube)
Liquid column
Liquid column
Process liquid
gauge valve

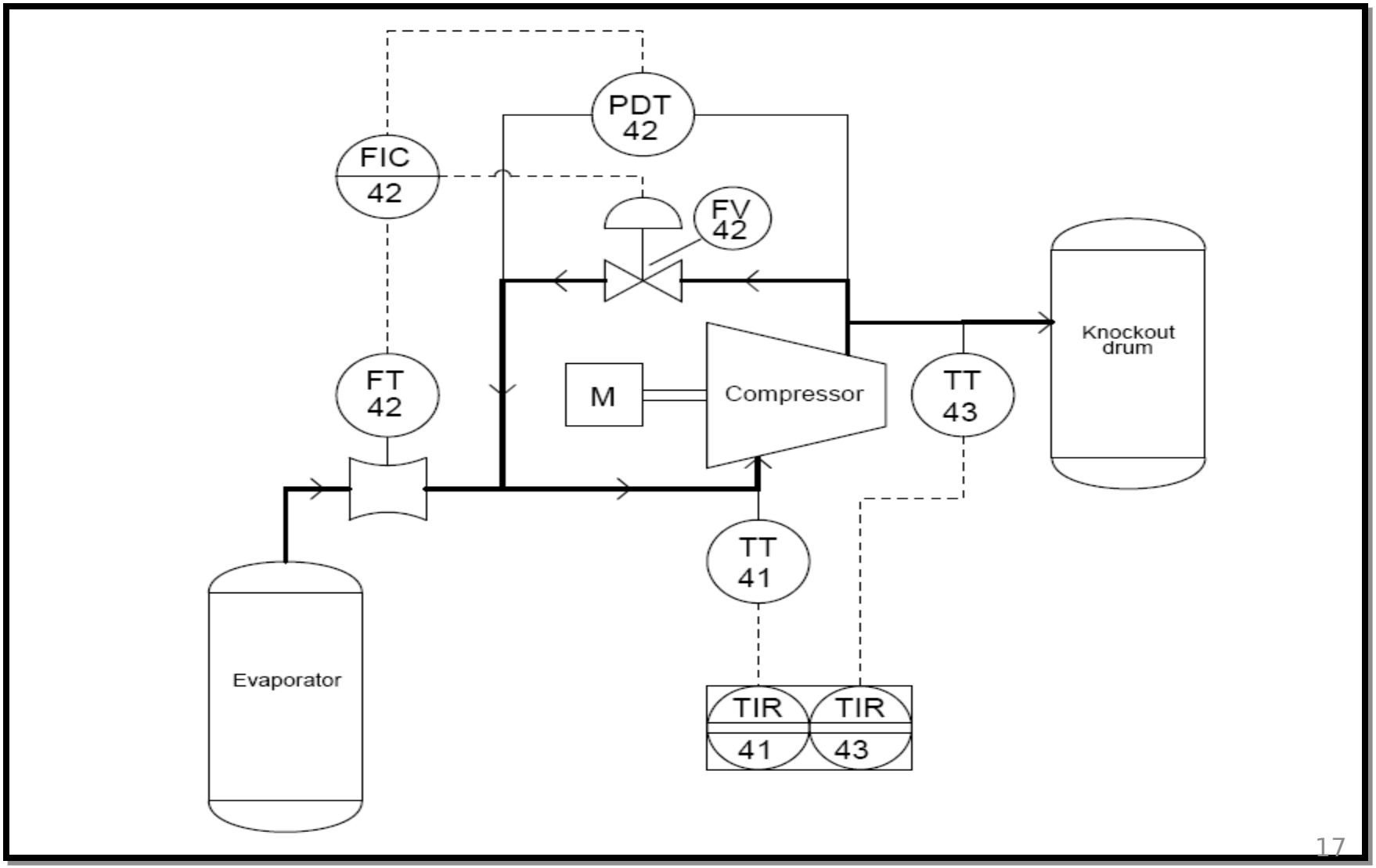
Bourdon Tube



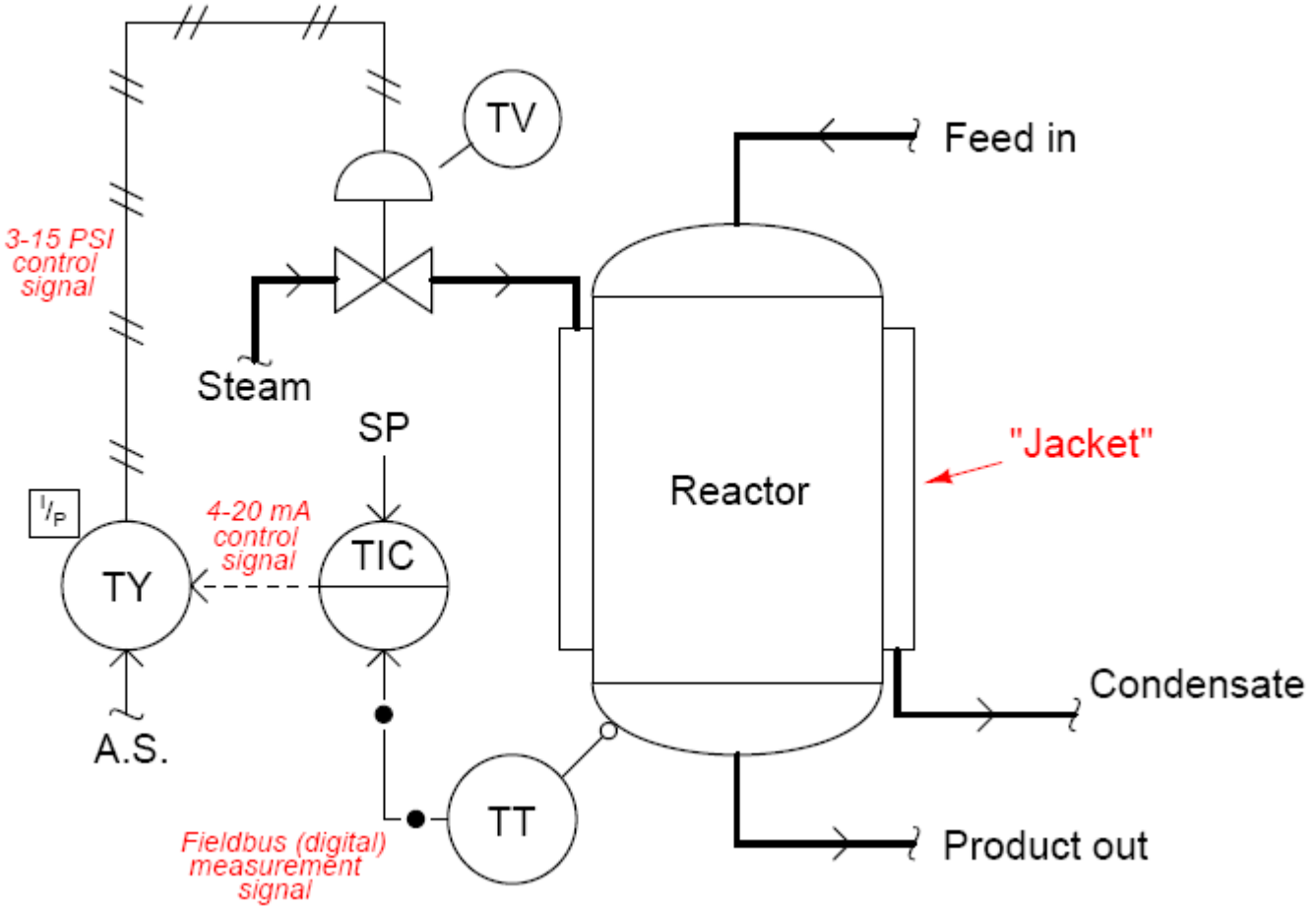
RTD (Resistance Temperature Detector)

Instruments in the Field

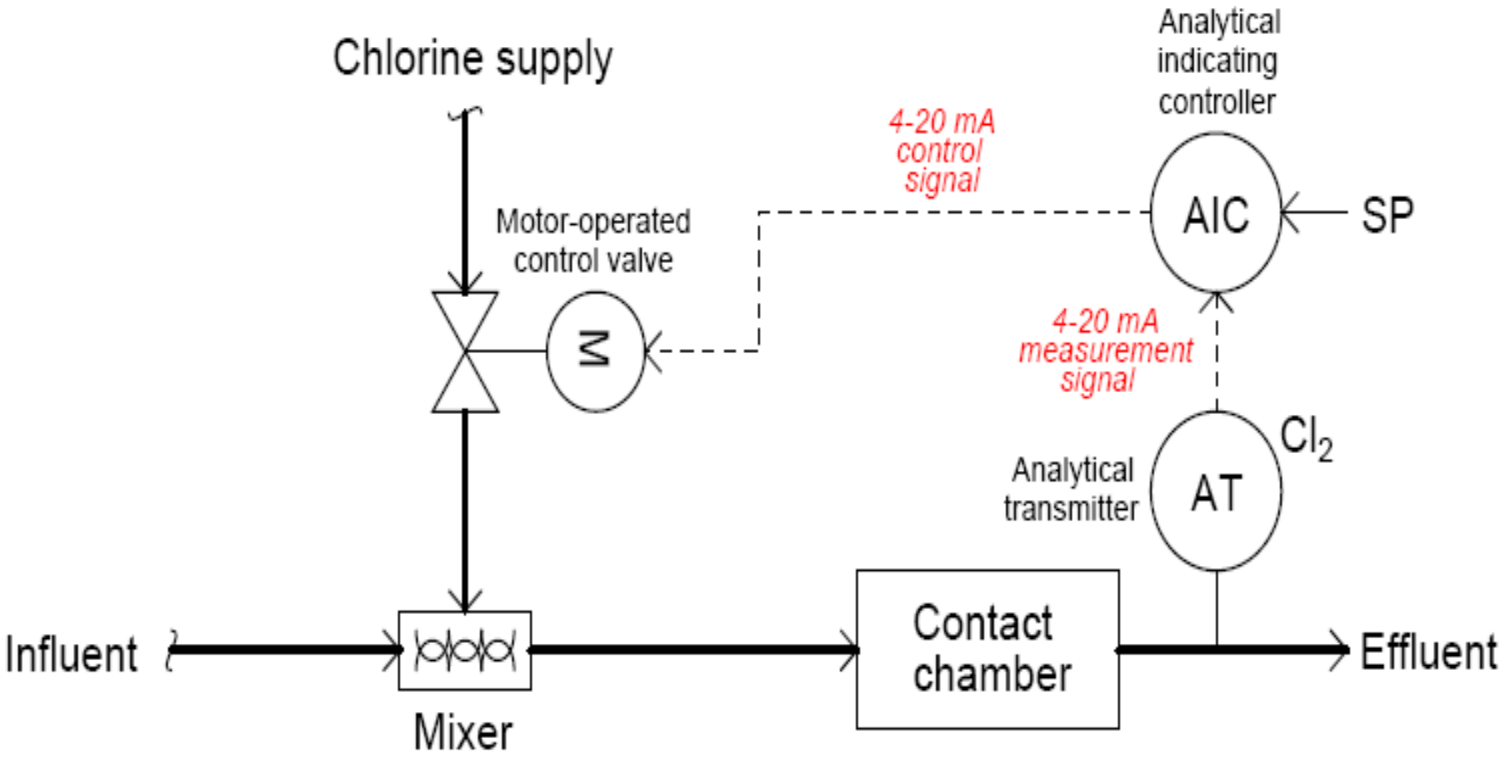
Process & Instrument Diagram



P&I Diagram: 2

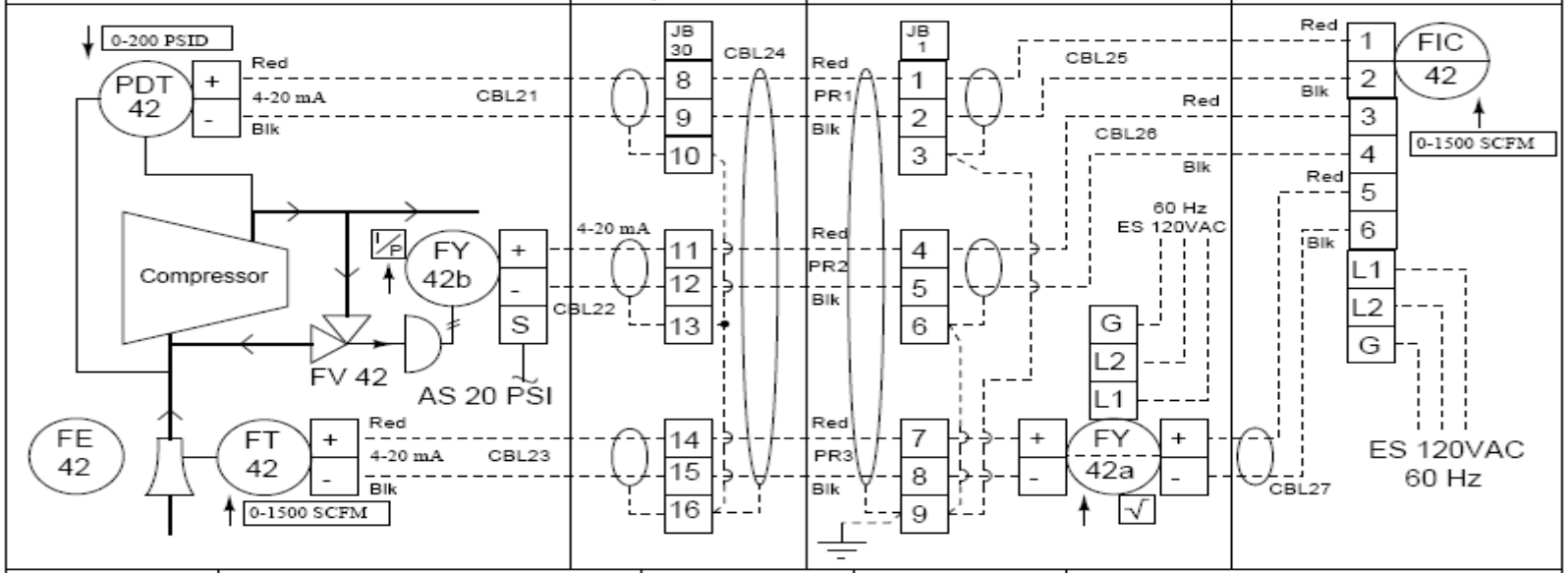

TV
Feed in
3-15 PSI
control
signal
Steam
SP
"Jacket"
Reactor
I/P
4-20 mA
control
signal
TY
TIC
Condensate
A.S.
TT
Fieldbus (digital)
measurement
signal
Product out

P&I Diagram: 3


Chlorine supply
Analytical indicating controller
4-20 mA control signal
Motor-operated control valve
AIC
SP
4-20 mA measurement signal
Cl2
Analytical transmitter
AT
Influent
Mixer
Contact chamber
Effluent

Loop Diagram

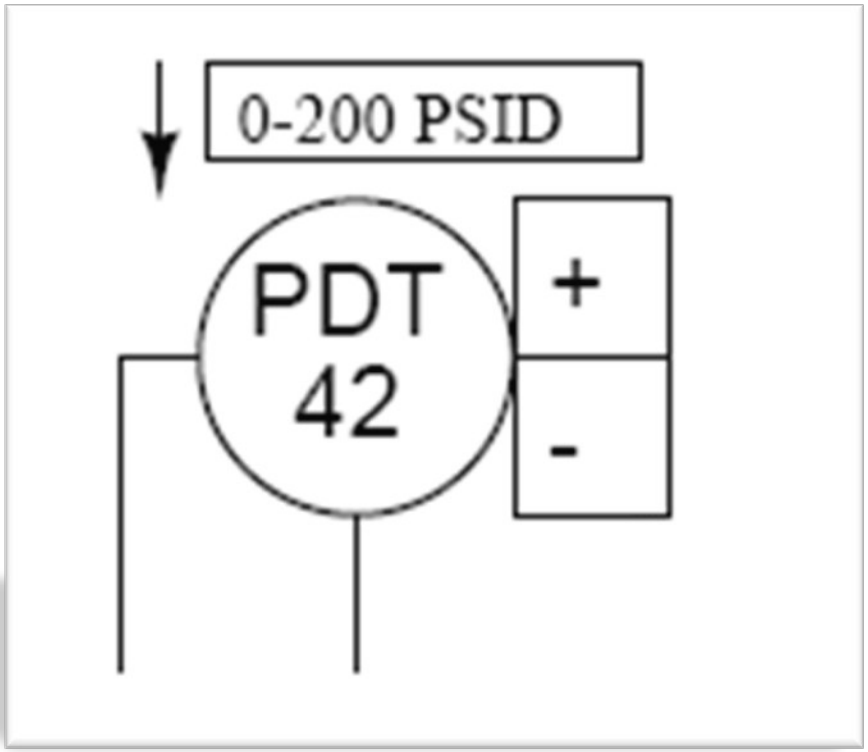
Loop Diagram: Compressor surge control — **Date:** April 1, 2003



Tag number	Description	Input cal.	Output cal.	Notes
FE 42	Venturi tube	0-1500 SCFM	0-100 "WC	
FT 42	Suction flow transmitter	0-100 "WC	4-20 mA	
FY 42a	Square root extractor	4-20 mA	4-20 mA	
FY 42b	Current-to-pressure converter	4-20 mA	3-15 PSI	
FV 42	Anti-surge control valve	3-15 PSI	100%-0%	Air-to-close
PDT 42	Differential pressure transmitter	0-200 PSI	20-4 mA	Reverse action
FIC 42	Anti-surge controller	4-20 mA	4-20 mA	

Reverse-Acting versus Direct-Acting Instrument

- Direct-acting instrument is one whose output signal increases as the input stimulus increases.
- Reverse-acting instrument is one whose output signal decreases as the input stimulus increases
- What is the advantage of using reverse-acting instrument?

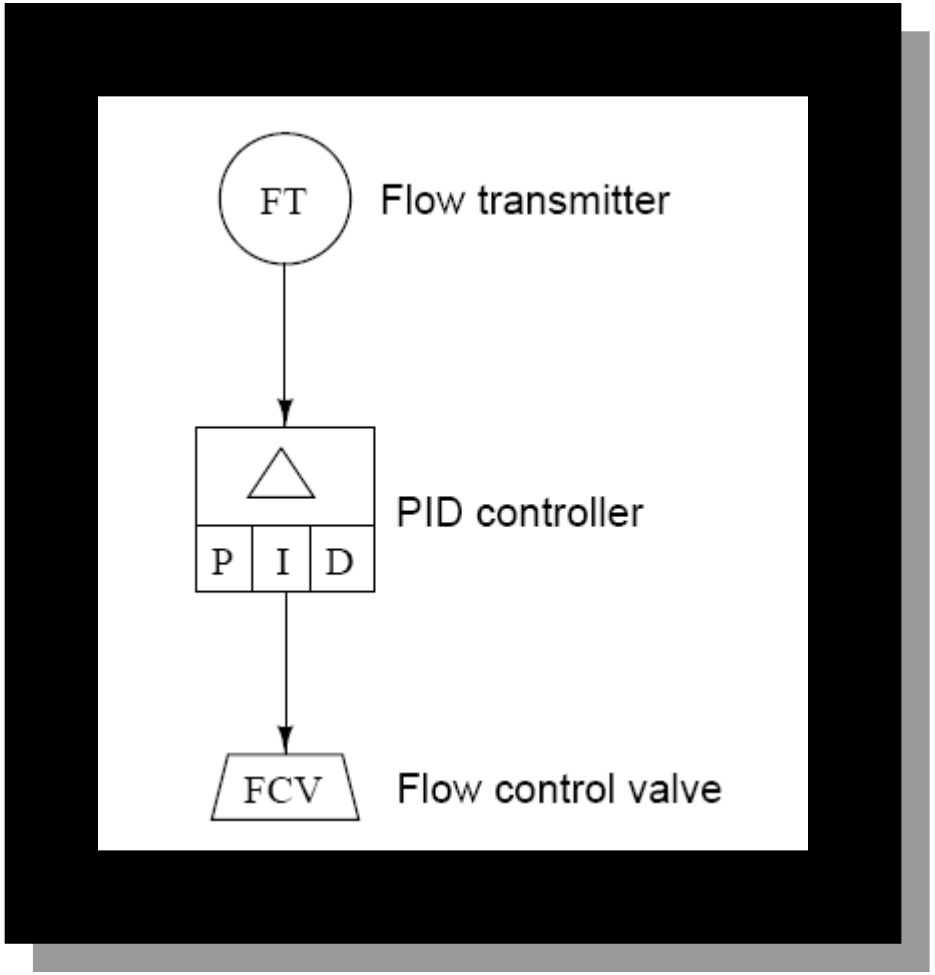


Advantage of using reverse-acting instrument

- A decreasing current signal will be interpreted by the controller as a high differential pressure. If any wire connection fails in the 4-20 mA current loop for that transmitter, the resulting 0 mA signal will be naturally “seen” by the controller as a pressure over-range condition.
- This is considered dangerous in a compressor system because it predicts a condition of surge. Thus, the controller will naturally take action to prevent surge by commanding the anti-surge control valve to open, because it “thinks” the compressor is about to surge. In other words, the transmitter is intentionally calibrated to be reverse-acting such that any break in the signal wiring will naturally bring the system to its safest condition.

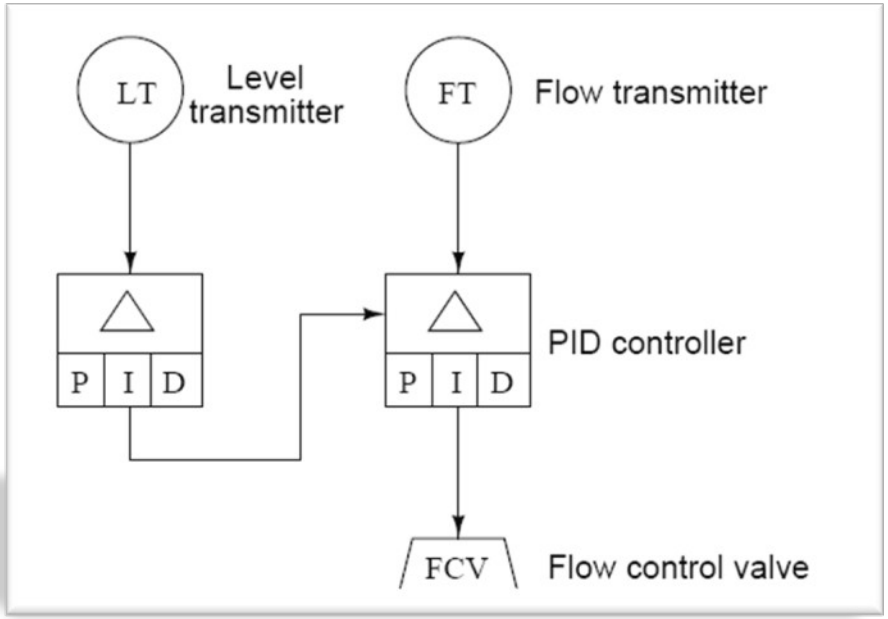
SAMA Diagram

- Scientific Apparatus Makers Association, referring to a unique form of diagram used primary in the power generation industry to document control strategies.

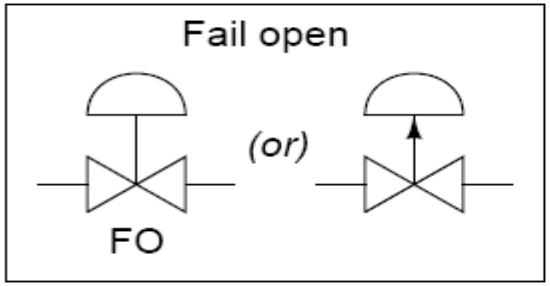


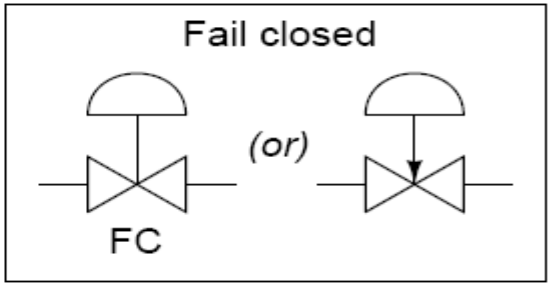
SAMA Diagram: Cascaded Control

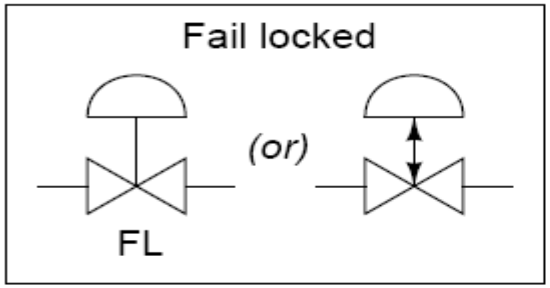
- A cascaded control system, where the output of one controller acts as the set point for another controller to follow, appears in SAMA diagram form like this:

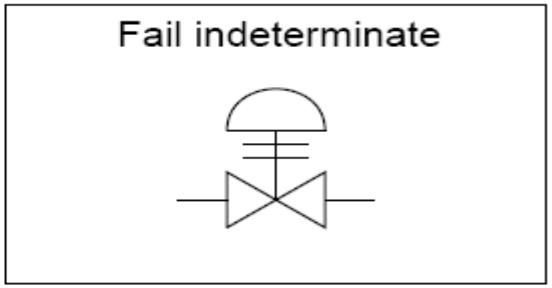


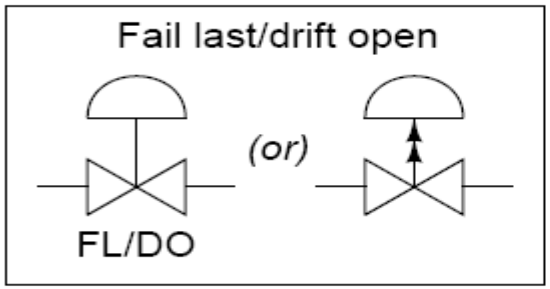
Valve Failure Modes

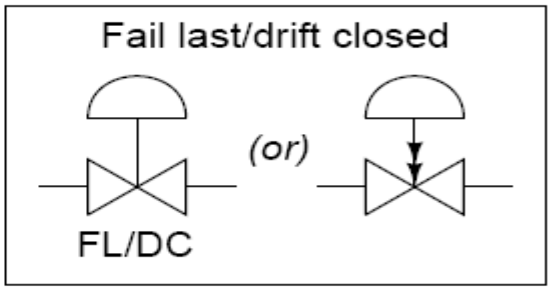












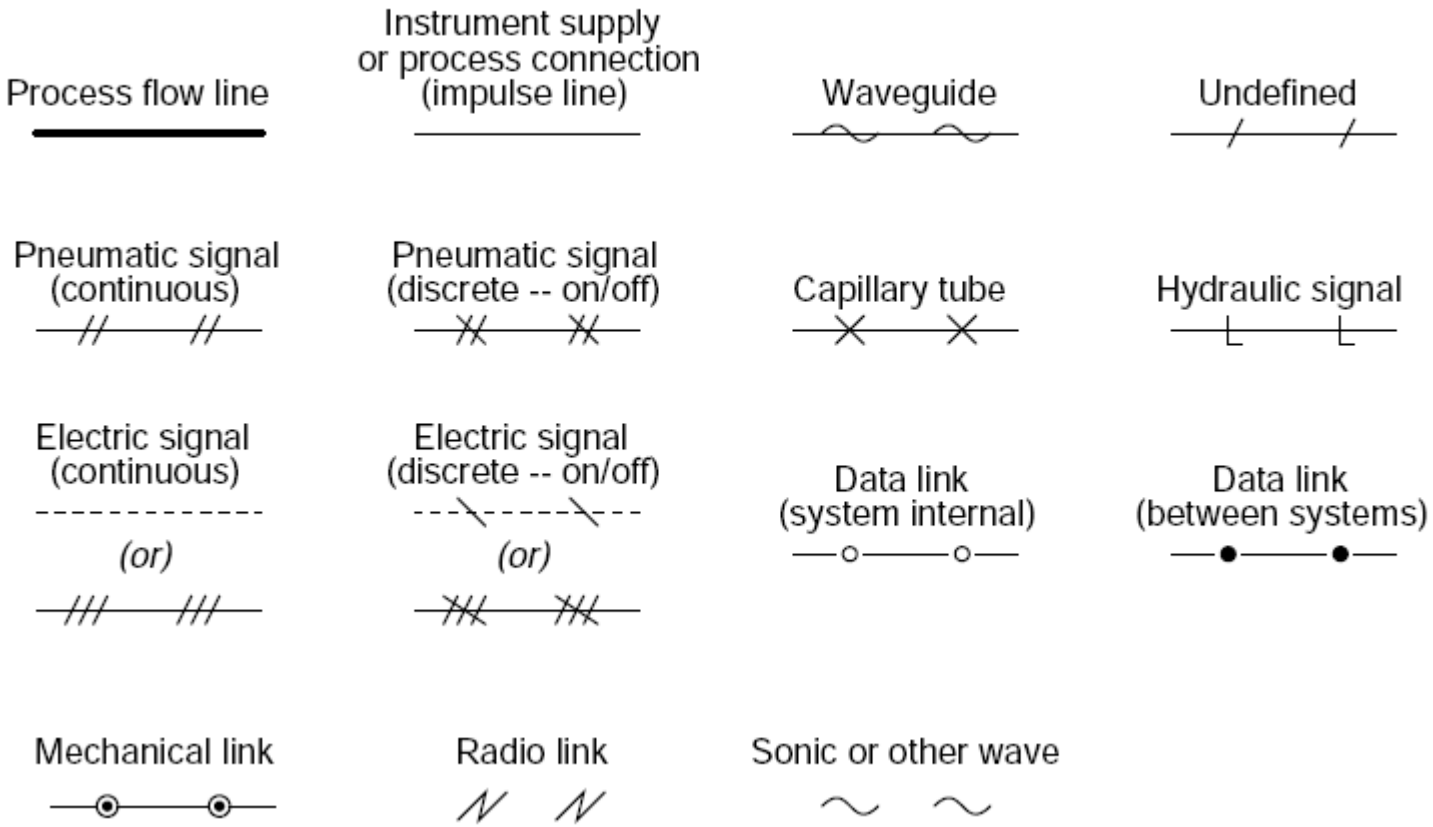
Instrumentation identification Tags

- FC-135
- 12-FC-135
- 12-FC-135A, 12-FC-135B, 12-FC-135C

Line Symbols (according to ISA 5.1 Standard)

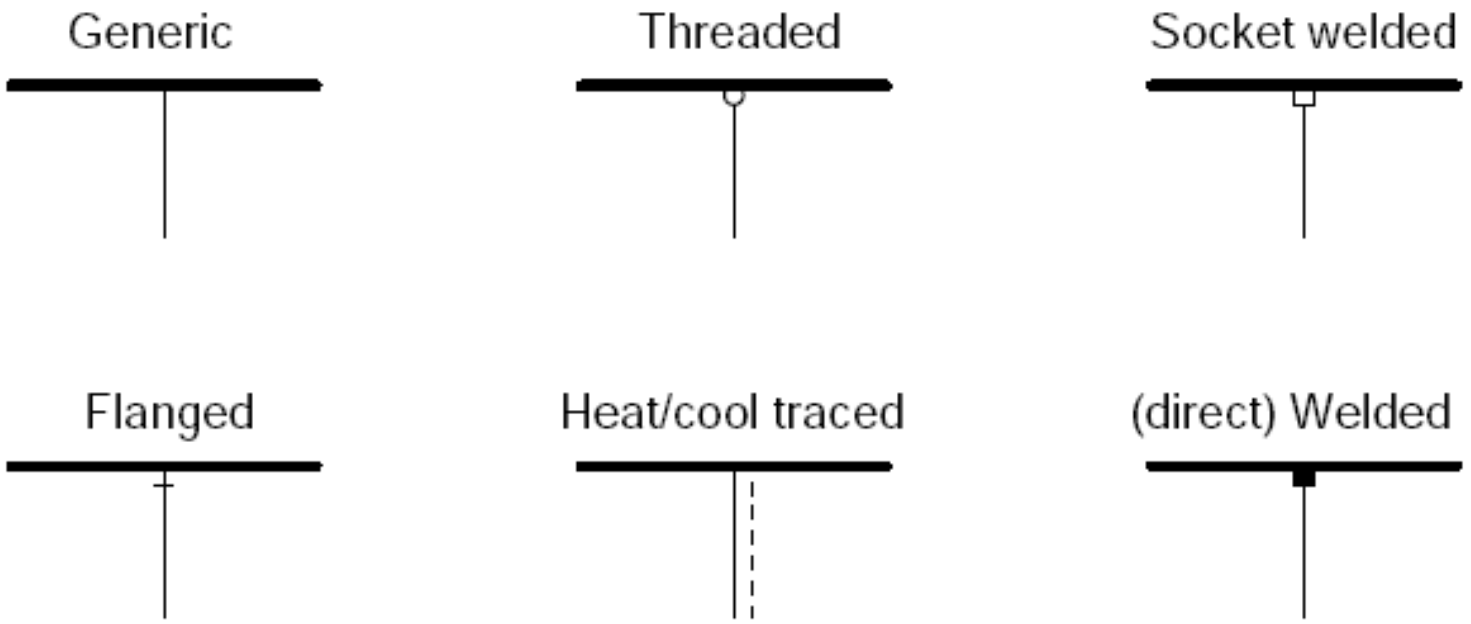
ISA: Instrument Society of America

7.5.1 Line types



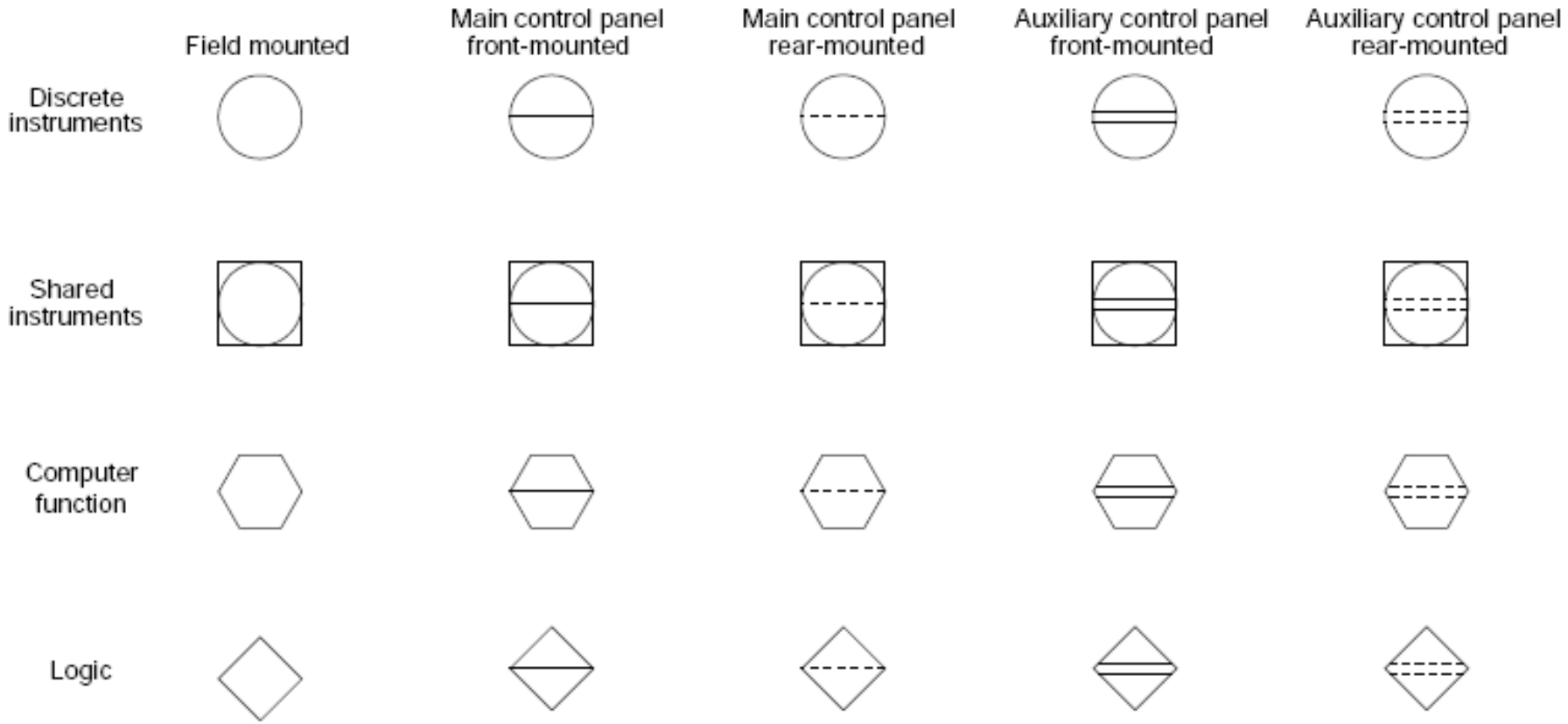
Reference: ISA 5.1

7.5.2 Process/Instrument line connections



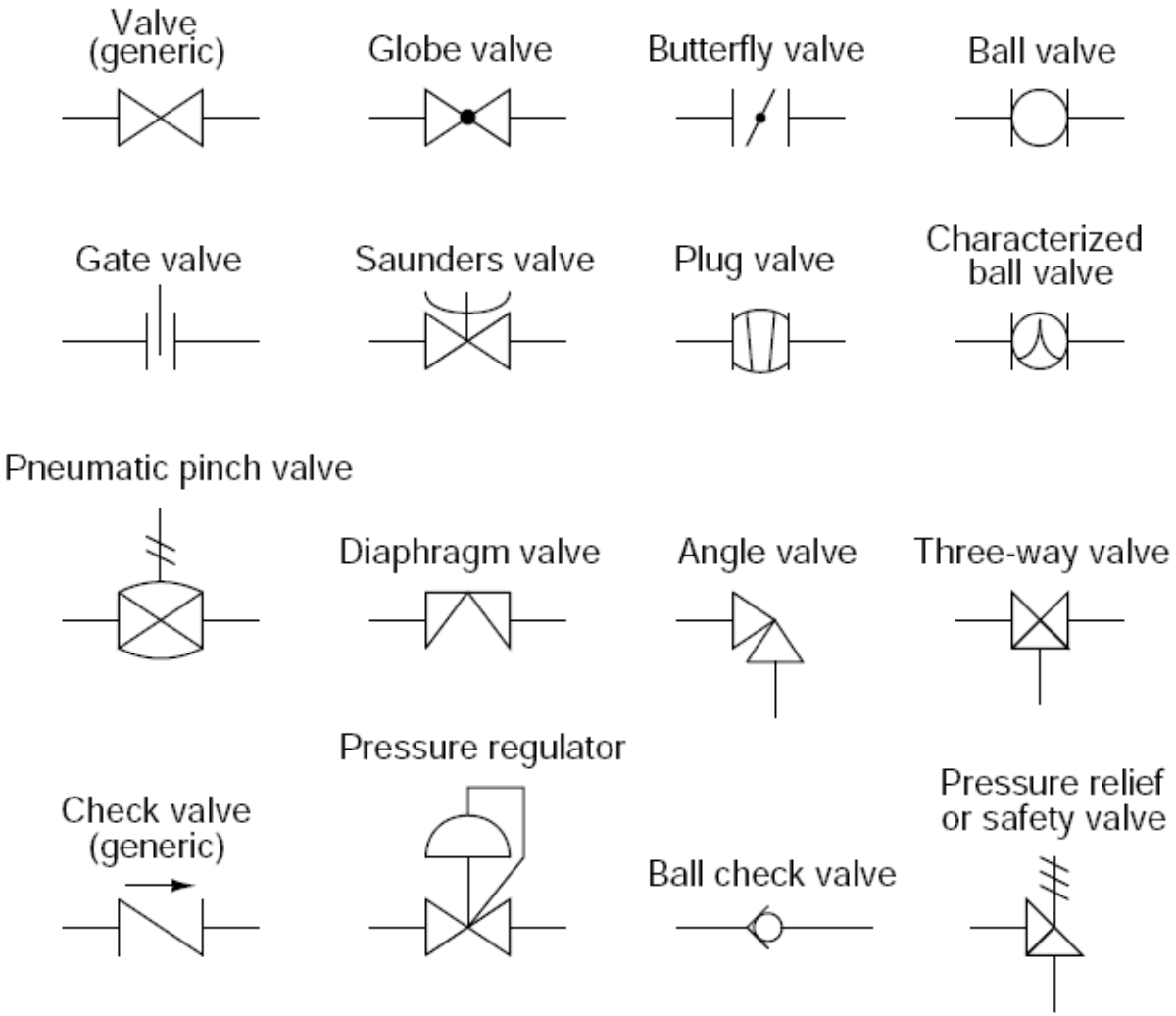
Reference: ISA 5.1

7.5.3 Instrument bubbles



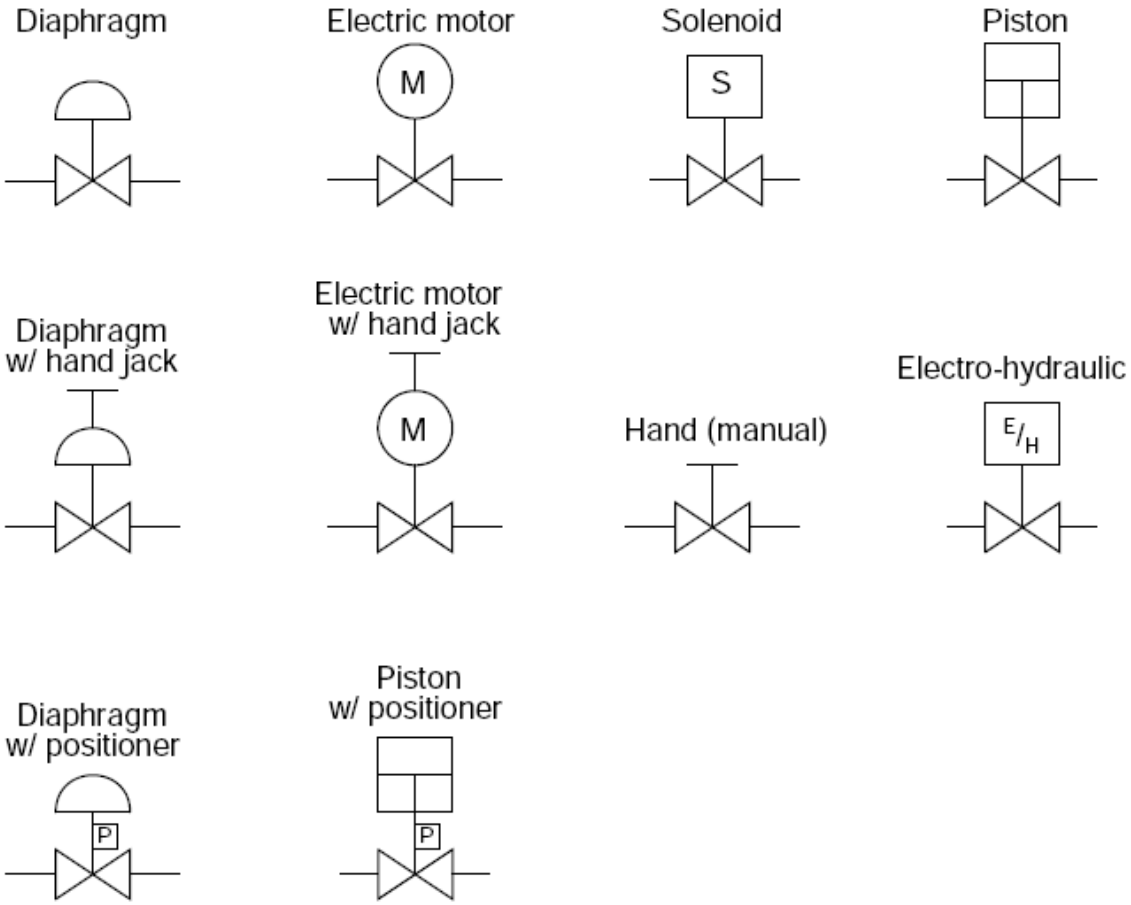
Reference: ISA 5.1

7.5.4 Process valve types



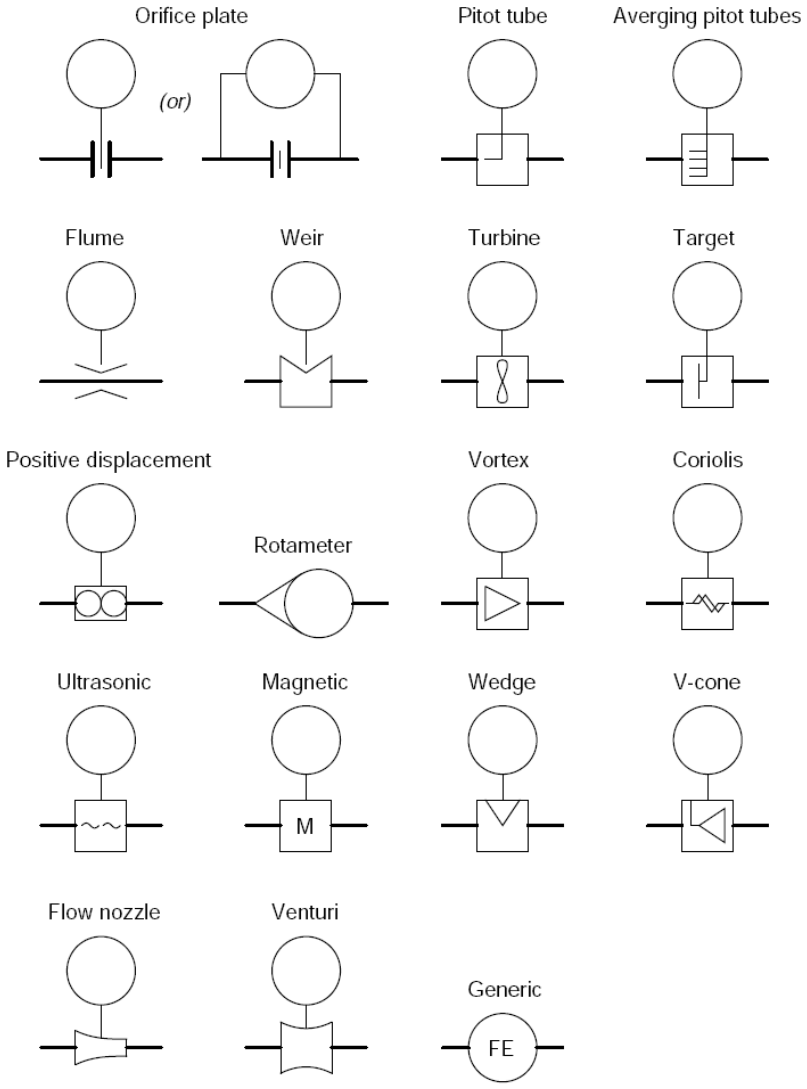
Reference: ISA 5.1

7.5.5 Valve actuator types

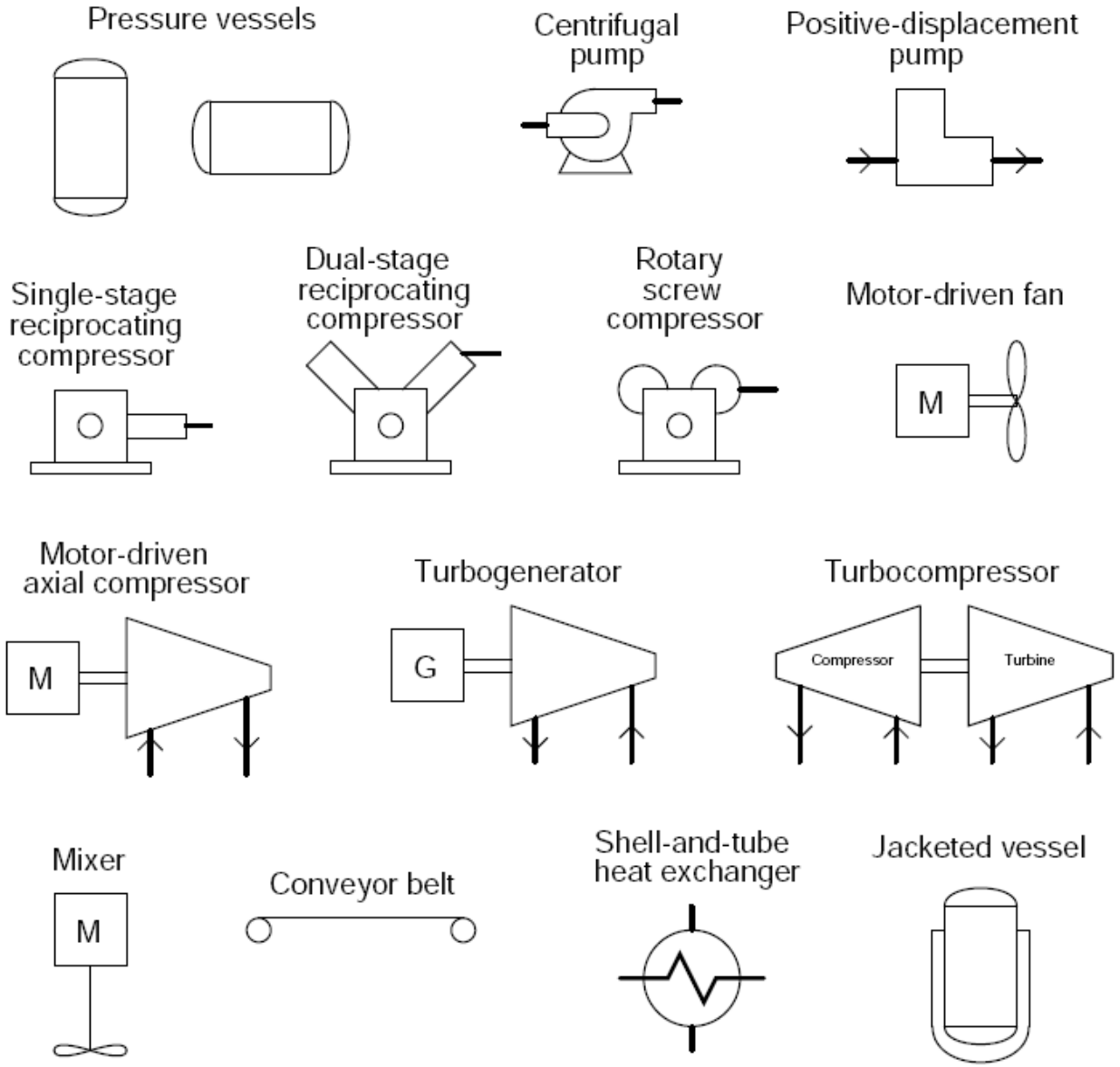


Reference: ISA 5.1

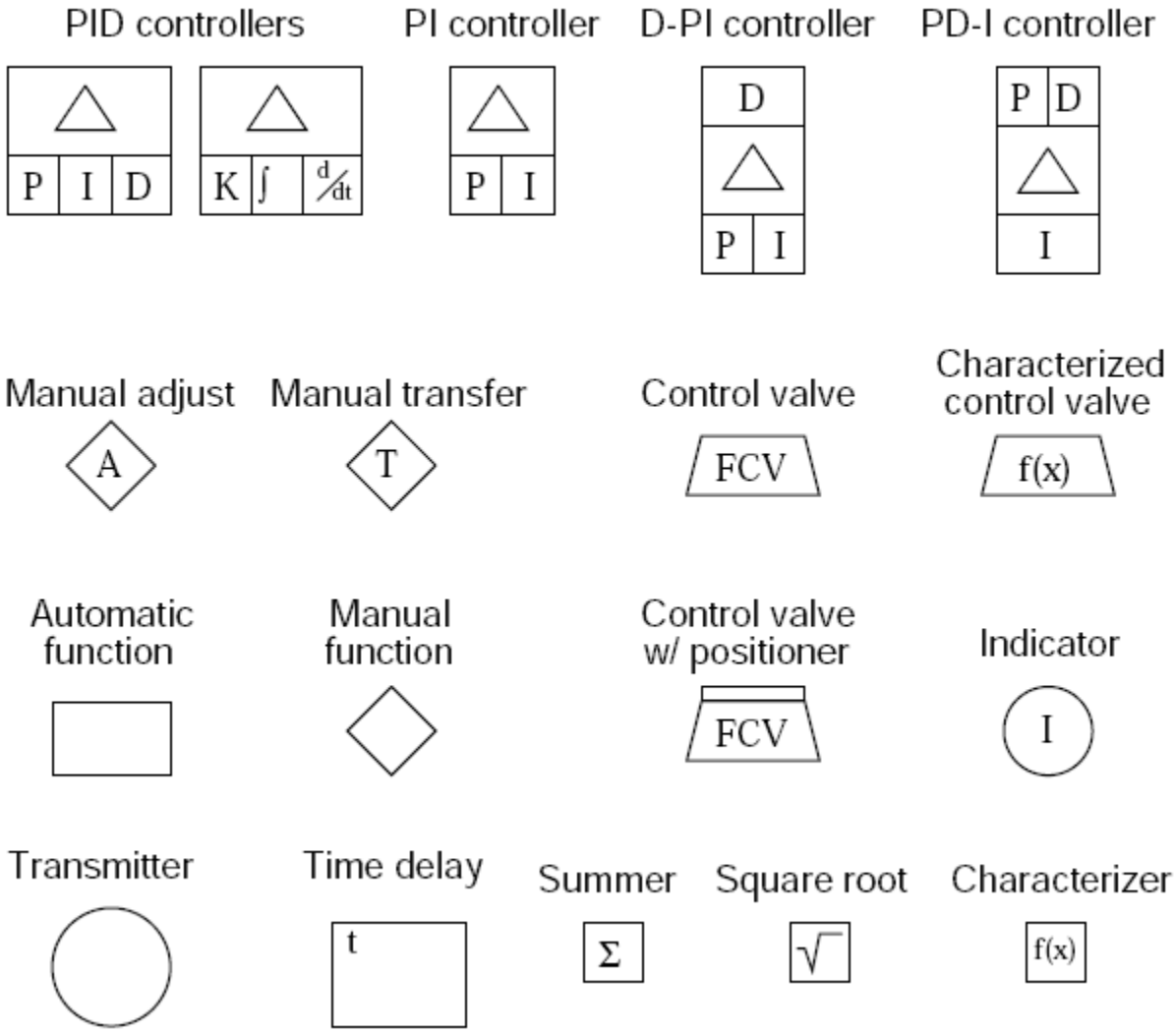
7.5.7 Flow measurement devices (flowing left-to-right)



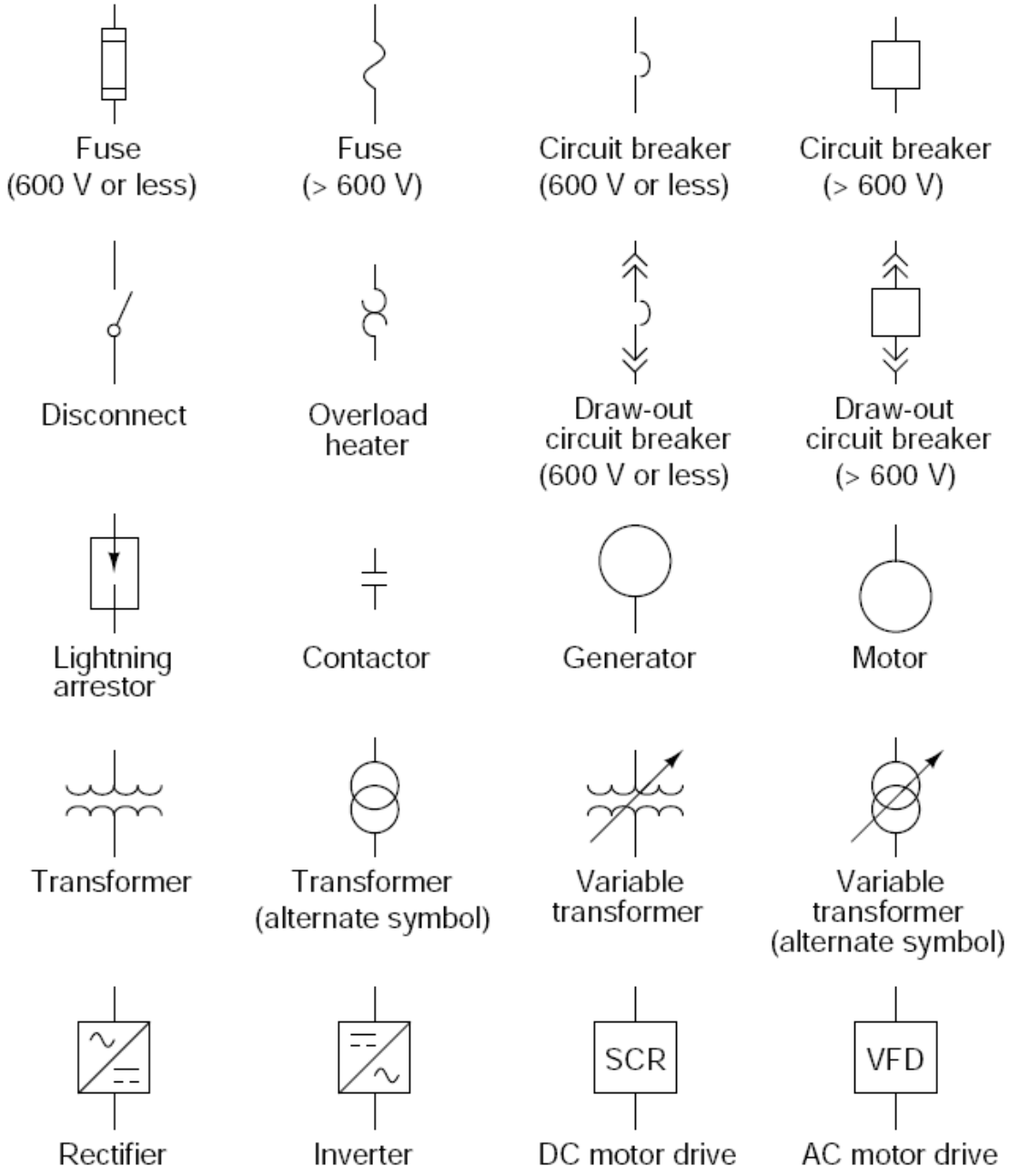
7.5.8 Process equipment



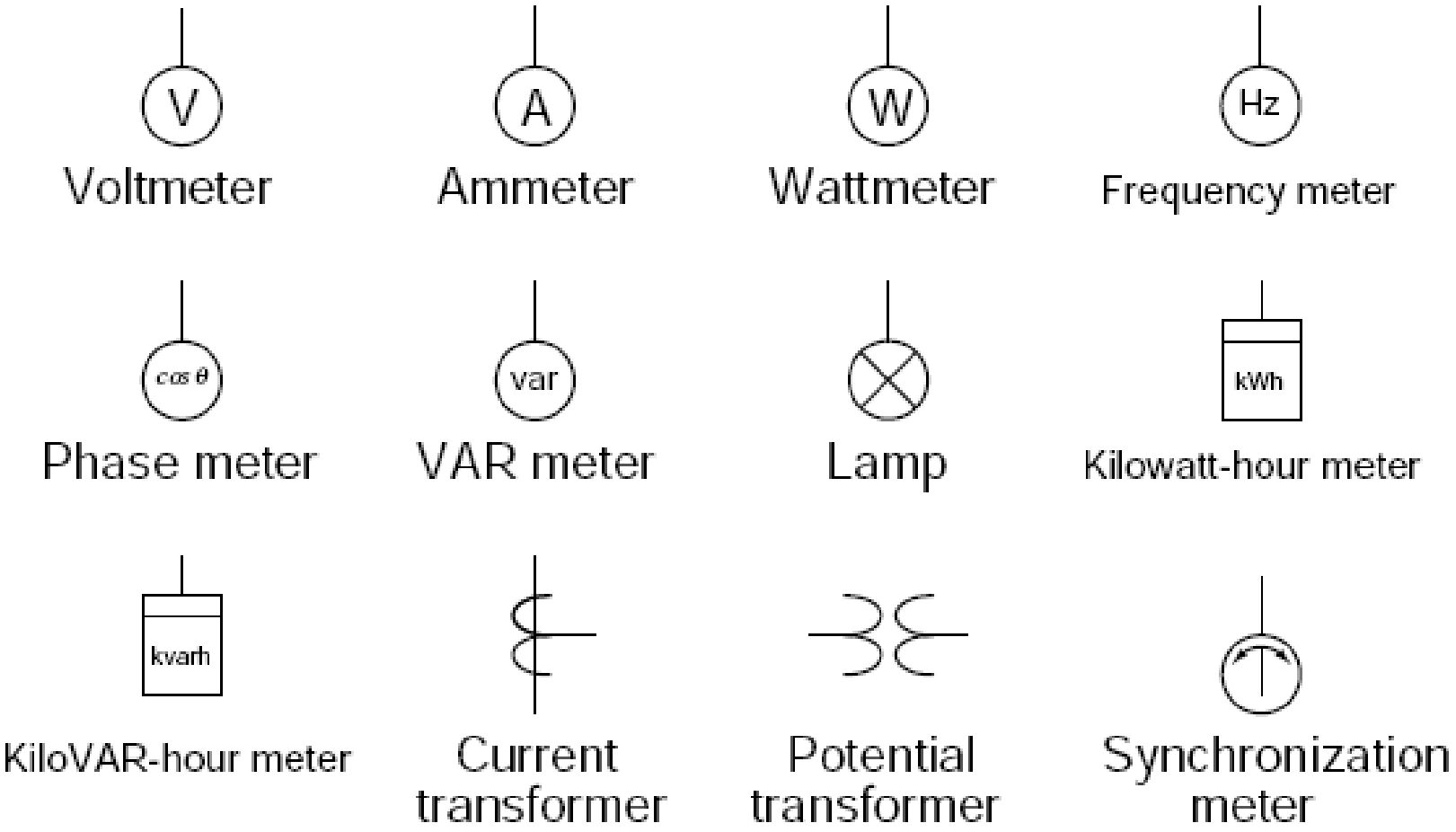
7.5.9 SAMA diagram symbols



7.5.10 Single-line electrical diagram symbols



Reference: ISA 5.1



Identification Tags

Letter	Variable	Modifier
A	Analytical (composition)	
B	Burner or Combustion	
C	*User-defined*	
D	*User-defined*	Differential
E	Voltage	
F	Flow	Ratio or Fraction
G	*User-defined*	
H	Hand (manual)	
I	Current	
J	Power	Scan
K	Time or Schedule	Time rate-of-change
L	Level	
M	*User-defined*	Momentary
N	*User-defined*	
O	*User-defined*	
P	Pressure or Vacuum	
Q	Quantity	Time-Integral or Total
R	Radiation	
S	Speed or Frequency	Safety
T	Temperature	
U	Multi-function	
V	Vibration	
W	Weight or Force	
X	*Unclassified*	X-axis
Y	Event, State, or Presence	Y-axis
Z	Position or Dimension	Z-axis

References

- “Commonly Used Electrical Symbols”, Eaton Electrical Inc., Eaton Corporation, Moon Township, PA, 2005.
- Instrumentation, Systems, and Automation Society Standards, 5.1-1984 (R1992), Instrumentation Symbols and Identification, Research Triangle Park, NC, 1984.
- Lipt´ak, B´ela G., Instrument Engineers’ Handbook – Process Measurement and Analysis Volume I, Fourth Edition, CRC Press, New York, NY, 2003.
- Lipt´ak, B´ela G., Instrument Engineers’ Handbook – Process Software and Digital Networks, Third Edition, CRC Press, New York, NY, 2002.

Control Room & Field Instrumentation

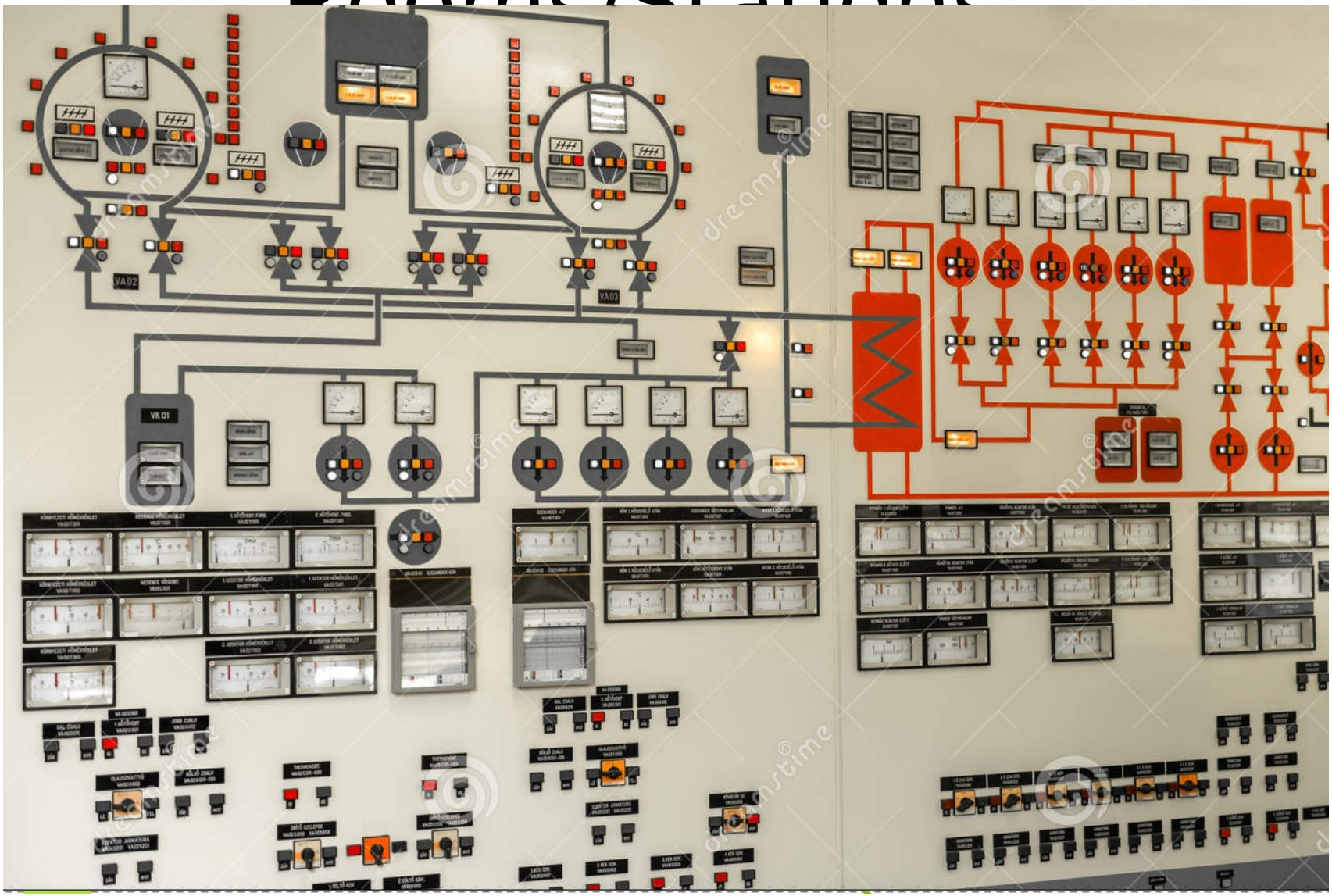
Typical Control Rooms/Stations

Typical Control Rooms/Stations

Typical Control Rooms/Stations

Typical Control Rooms/Stations

Typical Control Rooms/Stations



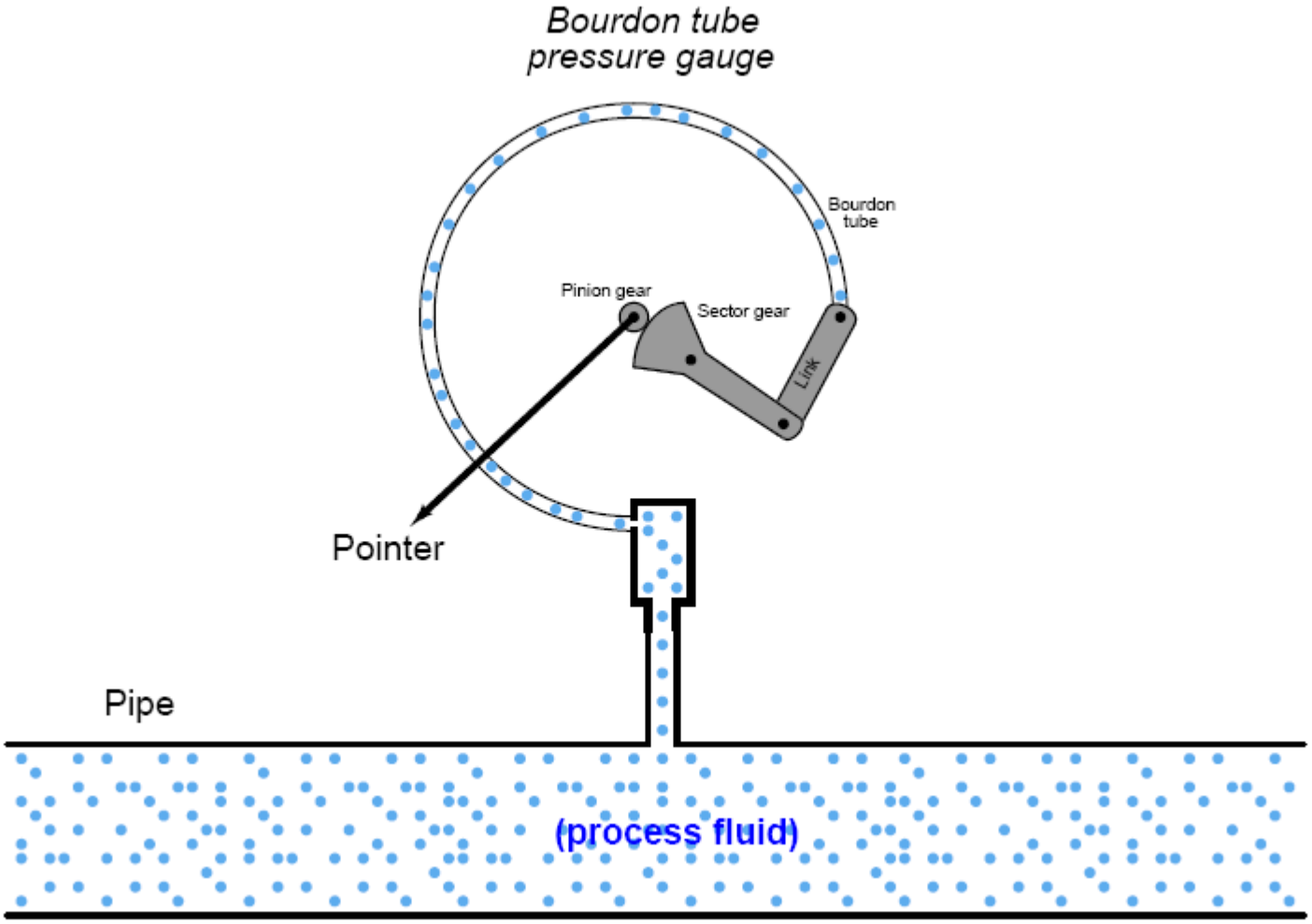
Categorization/Provisions of Control Room Instrumentation

- Indication panels
- Alarm panels
- Control panels
- Emergency trips
- Manipulation/programming consoles
- Visualization/trending consoles

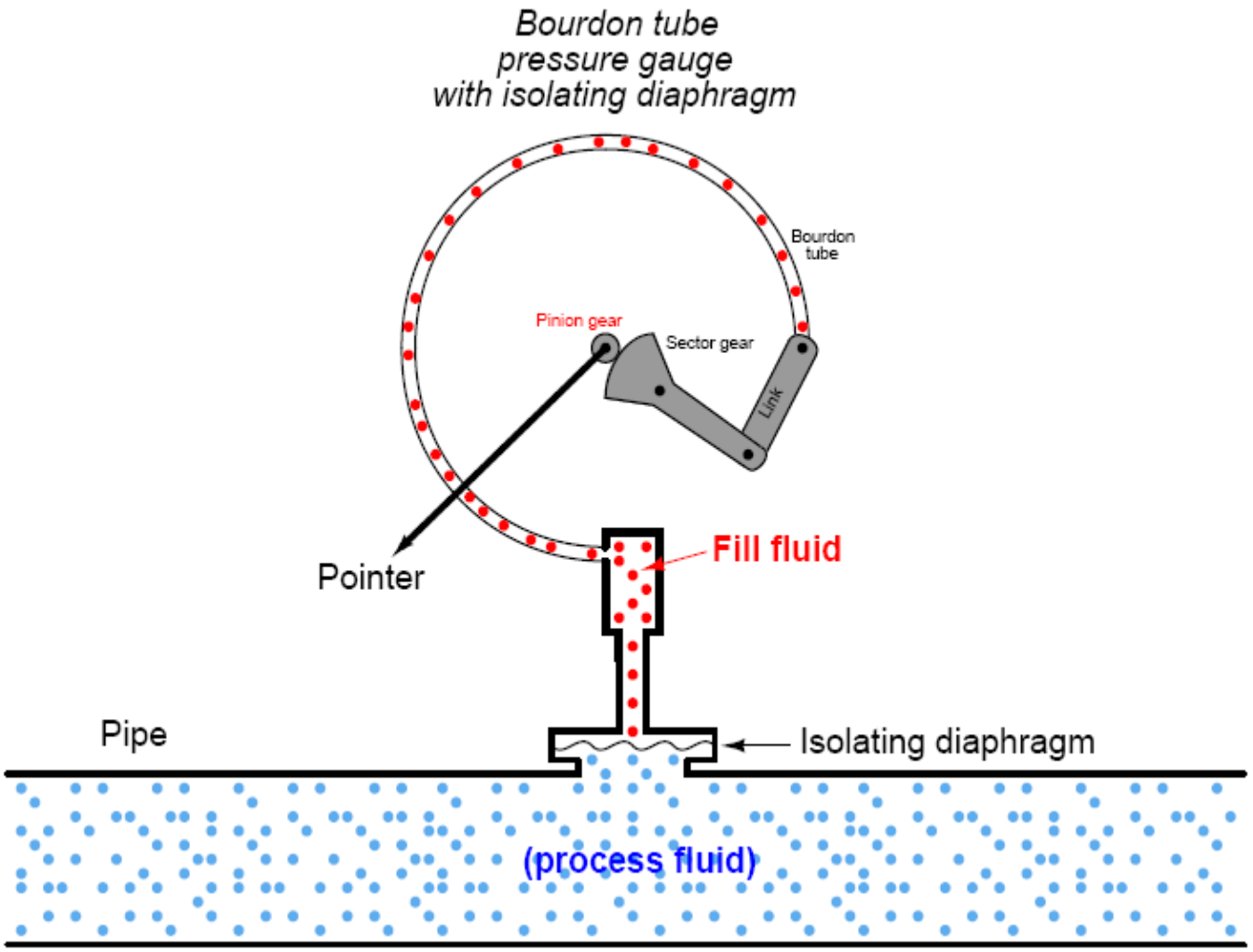
Typical Field Areas

- Solar Panel Manufacturing Plant

Field Instrumentation (1)



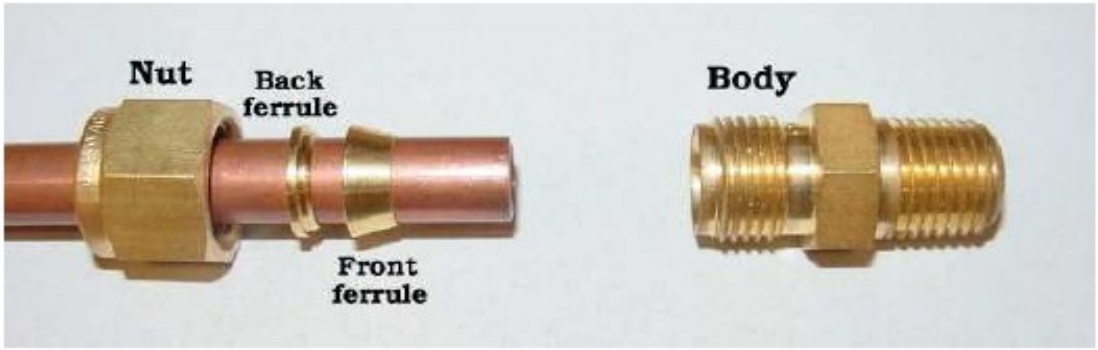
Field Instrumentation (2)



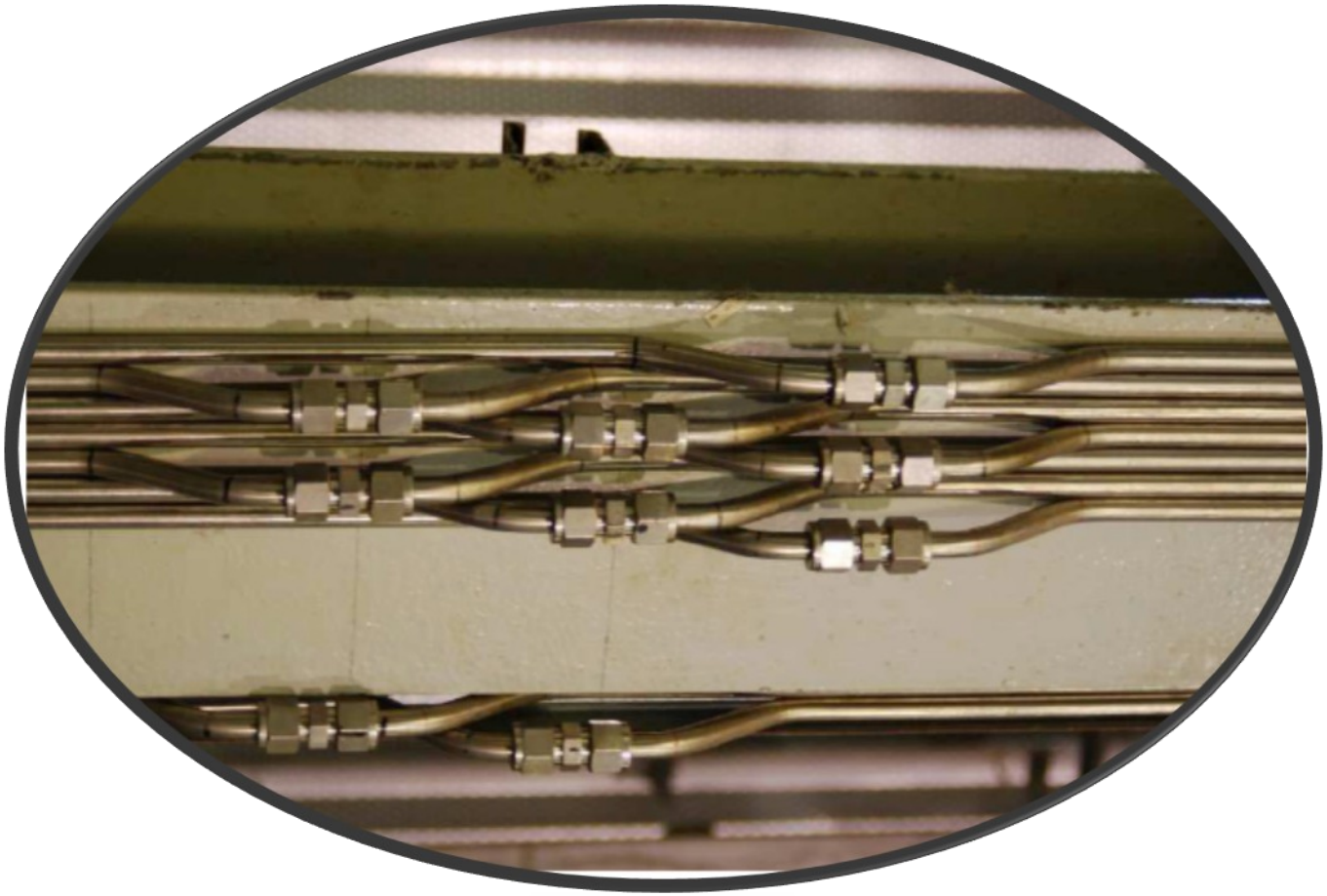
Pressure Transmitter installed on a water line

Ball Valve Fitted on the Line

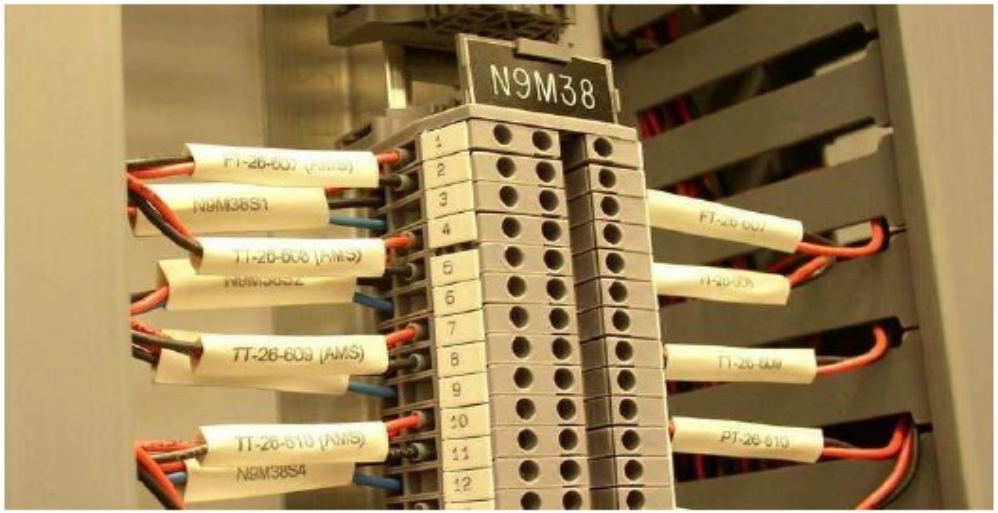
Control Fitting



Control Tubing: A Field View

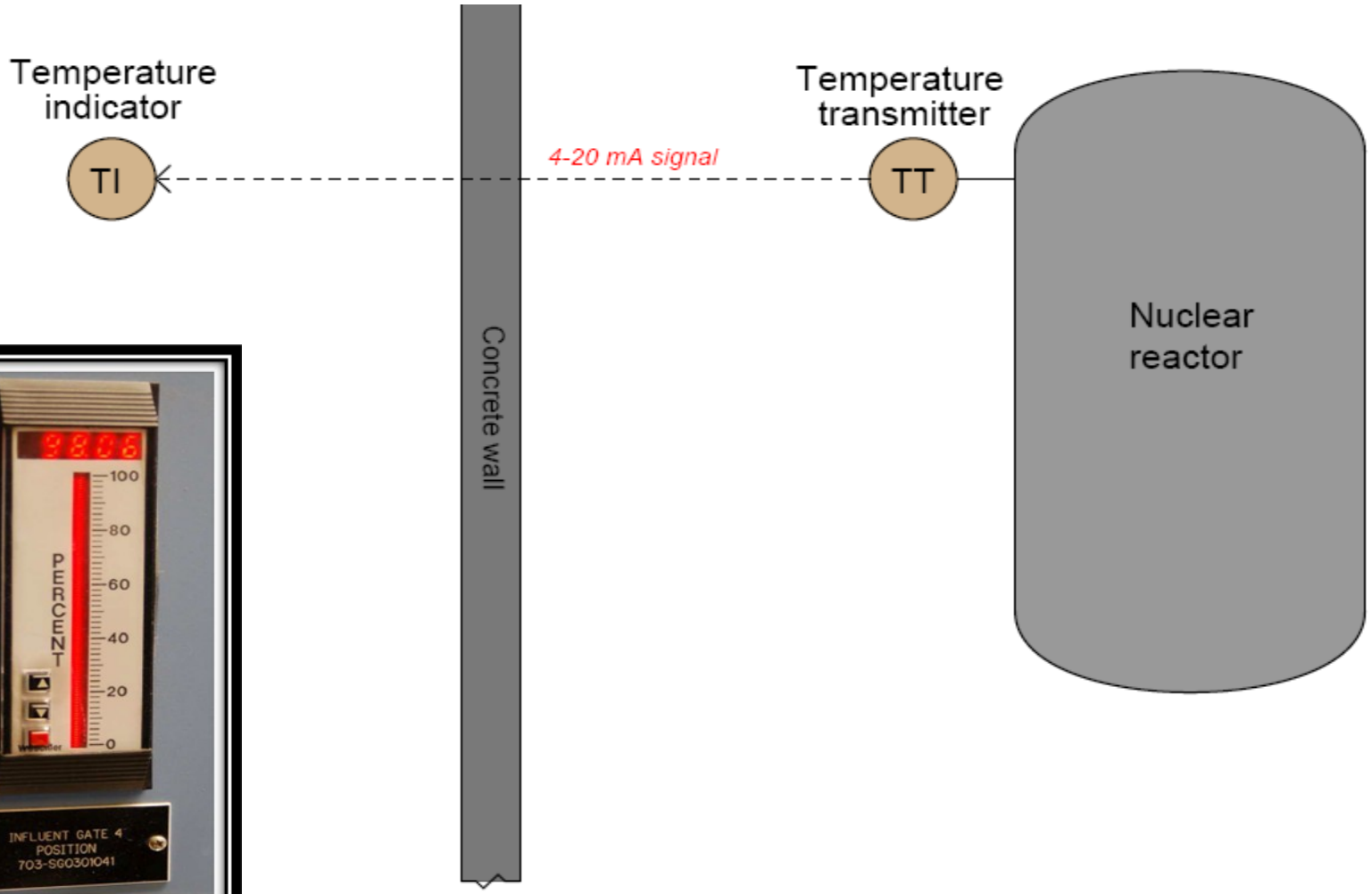


Control Wiring: A Field View

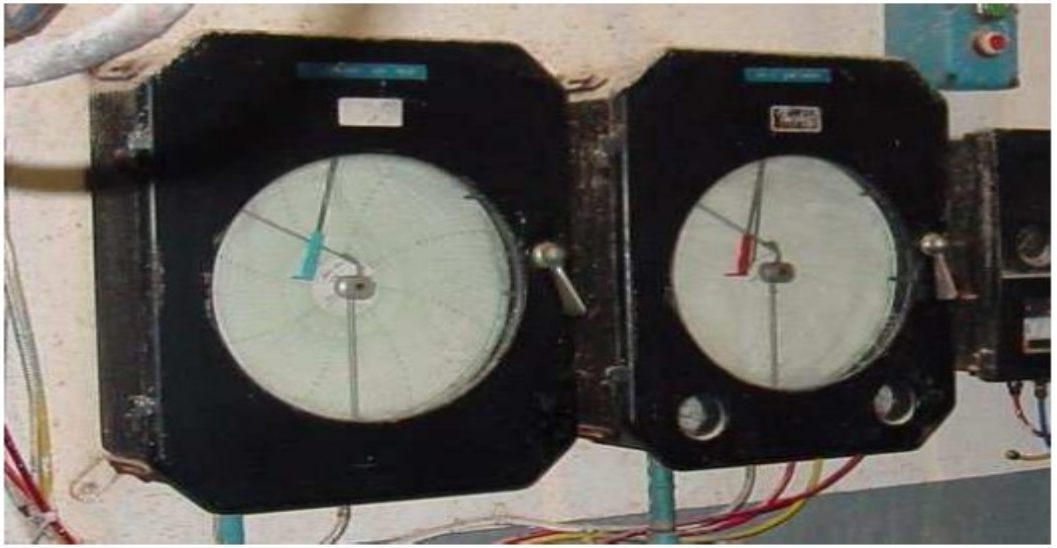


Indicators

9806
100
80
60
40
20
0
PERCENT
INFLUENT GATE 4
POSITION
703-SG0301041


Temperature
indicator
TI
4-20 mA signal
Temperature
transmitter
TT
Concrete wall
Nuclear
reactor

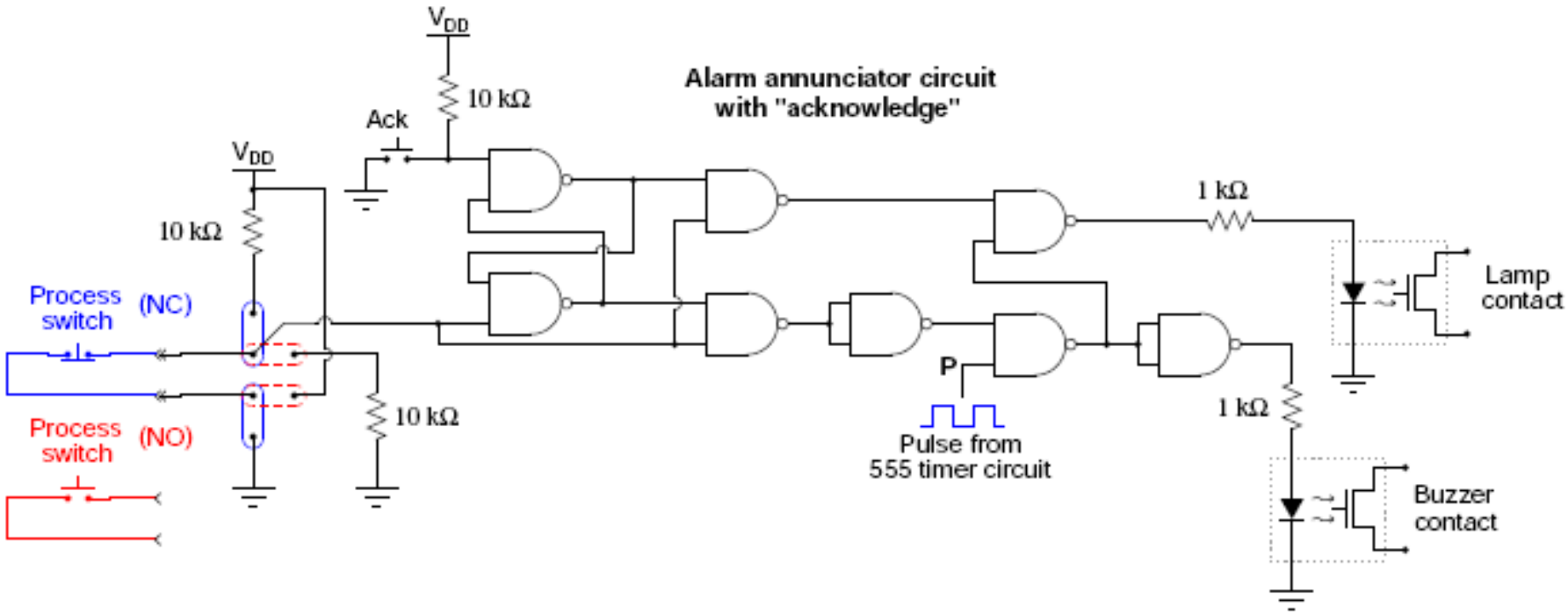
Recorder Charts



Annunciator Panel

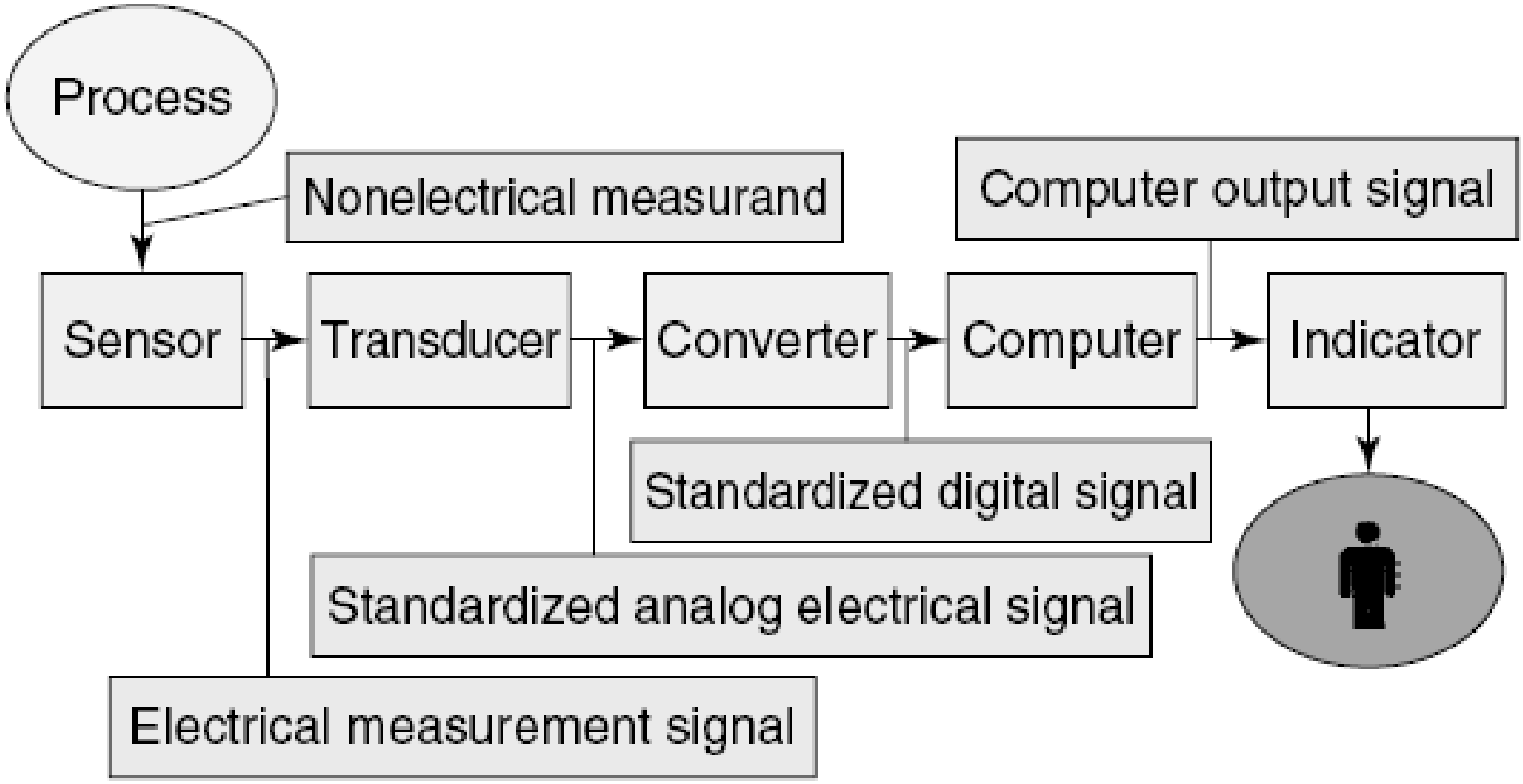
Inside the Annunciator Panel

Inside the Annunciator Relay Module



Errors in Measurement
Lecture # 8

Measurement Chain



Errors in Measurement Chain

If the measurement system has the general structure given in Figure 1, the following errors may appear for a general measurement task:

- input error
- sensor error
- signal transmission error 1
- transducer error
- signal transmission error 2
- converter error
- signal transmission error 3
- computer error
- signal transmission error 4
- indication error.

Error Classification

- Engineering classification
  - Systematic error
  - Random error
- ISO classification
  - Type A
  - Type B

Type A & Type B Errors

Type A uncertainty in the measurement result is expressed as a deviation evaluated by the method of statistical analysis from a series of observations.

Type B uncertainty in the measurement result is expressed as a deviation evaluated by methods other than the statistical analyses of series of observations.

- For TYPE B: Manufacturer's data may be used

Propagation of Error: Addition/Subtraction

1 Addition or Subtraction

If Q is some combination of sums and differences, i.e.

$$Q = a + b + \cdots + c - (x + y + \cdots + z), \tag{1}$$

then

$$\boxed{\delta Q = \sqrt{(\delta a)^2 + (\delta b)^2 + \cdots + (\delta c)^2 + (\delta x)^2 + (\delta y)^2 + \cdots + (\delta z)^2}.} \tag{2}$$

In words, this means that the uncertainties add *in quadrature* (that's the fancy math word for the square root of the sum of squares). In particular, if $Q = a + b$ or $a - b$, then

$$\boxed{\delta Q = \sqrt{(\delta a)^2 + (\delta b)^2}.} \tag{3}$$

Propagation of Error

Example: suppose you measure the height H of a door and get 2.00 ± 0.03 m. This means that $H = 2.00$ m and $\delta H = 0.03$ m. The door has a knob which is a height $h = 0.88 \pm 0.04$ m from the bottom of the door. Then the distance from the doorknob to the top of the door is $Q = H - h = 1.12$ m. What is the uncertainty in Q? Using equation (3),

$$\begin{aligned} \delta Q &= \sqrt{(\delta H)^2 + (\delta h)^2} && (4) \\ &= \sqrt{(0.03 \text{ m})^2 + (0.04 \text{ m})^2} && (5) \\ &= \sqrt{0.0009 \text{ m}^2 + 0.0016 \text{ m}^2} && (6) \\ &= \sqrt{0.0025 \text{ m}^2} = 0.05 \text{ m}. && (7) \end{aligned}$$

So $Q = 1.12 \pm 0.05$ m.

Propagation of Error: Multiplication/Division

2 Multiplication or Division

If

$$Q = \frac{ab\cdots c}{xy\cdots z}, \tag{12}$$

then

$$\frac{\delta Q}{|Q|} = \sqrt{\left(\frac{\delta a}{a}\right)^2 + \left(\frac{\delta b}{b}\right)^2 + \cdots + \left(\frac{\delta c}{c}\right)^2 + \left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta y}{y}\right)^2 + \cdots + \left(\frac{\delta z}{z}\right)^2}. \tag{13}$$

What this means is that the *fractional uncertainties* add in quadrature. In practice, it is usually simplest to convert all of the uncertainties into *percentages* before applying the formula.

Propagation of Error

Example: a bird flies a distance $d = 120 \pm 3$ m during a time $t = 20.0 \pm 1.2$ s. The average speed of the bird is $v = d/t = 6$ m/s. What is the uncertainty of v?

$$\frac{\delta v}{v} = \sqrt{\left(\frac{\delta d}{d}\right)^2 + \left(\frac{\delta t}{t}\right)^2} \tag{14}$$

$$= \sqrt{\left(\frac{3\text{ m}}{120\text{ m}}\right)^2 + \left(\frac{1.2\text{ s}}{20.0\text{ s}}\right)^2} \tag{15}$$

$$= \sqrt{(2.5\%)^2 + (6\%)^2} \tag{16}$$

$$= \sqrt{0.000625 + 0.0036} = 6.5\%. \tag{17}$$

$$\begin{aligned} \delta v &= v(6.5\%) \\ &= (6\text{ m/s})(6.5\%) \\ &= 0.39\text{ m/s}. \end{aligned}$$

Limits of an Error

$$Y = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-\frac{1}{2}\left(X-\mu\right)^2 / \sigma^2}$$

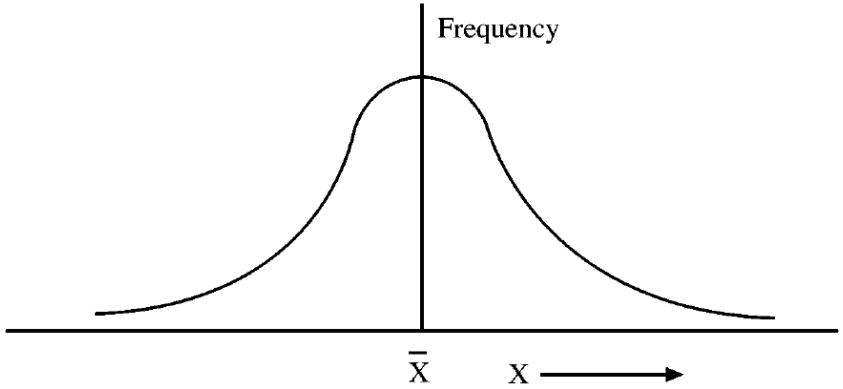


FIGURE 4.1

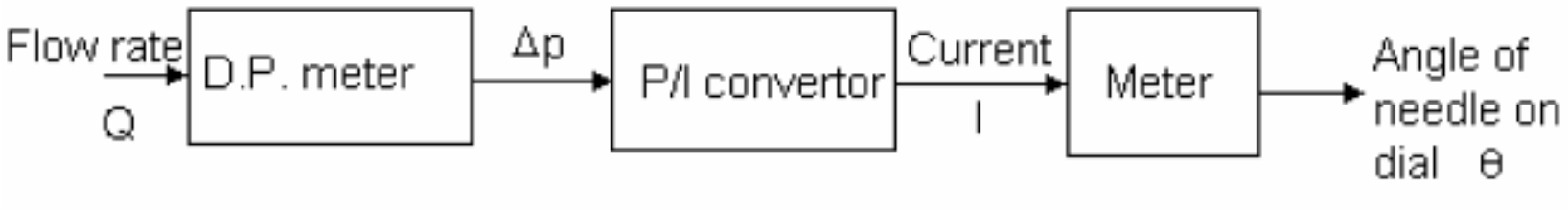
where X = the input variable, here the value obtained by a measurement
μ = the average of the population of the X variable
σ = the standard deviation of the population, expressed as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(X_i - \mu\right)^2}{n}}$$

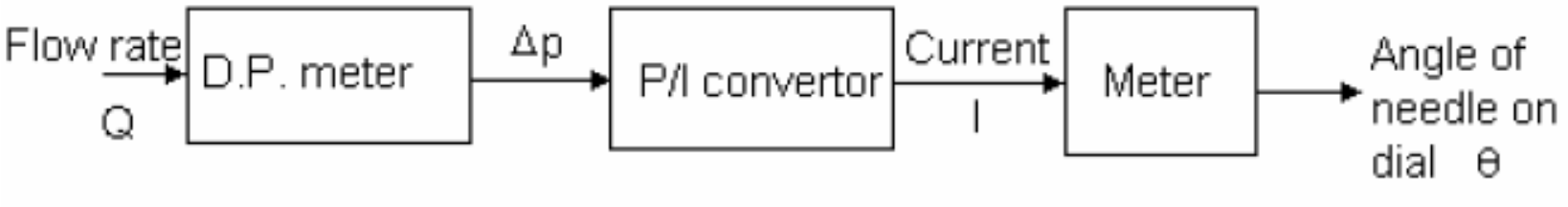
where X_i = the i^{th} X measurement
n = the number of data points measured from the population

Pre-Calibration Calculations

Example Problem



Example Problem

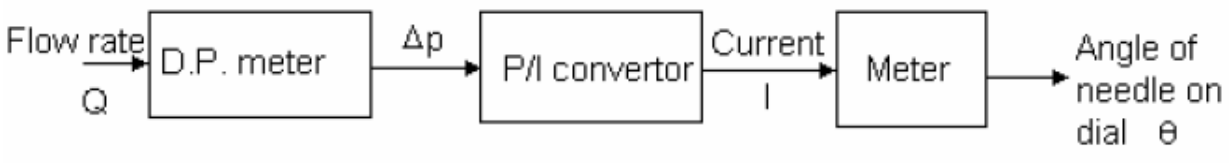


The equations for each sub system in the above system is as follows.

Flow meter	$\Delta p = 2 \times 10^6 Q^2$ where p is in bar and Q is m^3/s.
P/I converter	$I = 20 \Delta p$ where I is mA and p is in bars.
Ammeter	$\theta = 14 I$ where θ is in degrees and I in mA.

Calculate the output angle if the flow rate is 0.0004 m^3/s.

Example Problem



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Ammeter	$\theta = 14 I$ where θ is in degrees and I in mA.

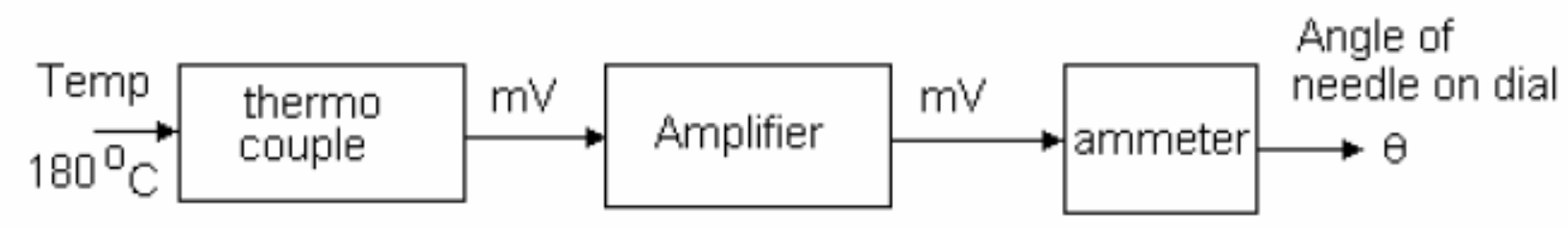
Calculate the output angle if the flow rate is 0.0004 m^3/s.

STEP 1
Calculate the differential pressure.
$\Delta p = 2 \times 10^6 Q^2 = 2 \times 10^6 (0.0004)^2 = 0.32$ bar

STEP 2
Calculate the current.
$I = 20\Delta p = 20 \times 0.32 = 6.4$ mA

STEP 3
Calculate the angle of the needle on the dial.
$\theta = 140 I = 14 \times 6.4 = 89.6^o$.

Practice Example



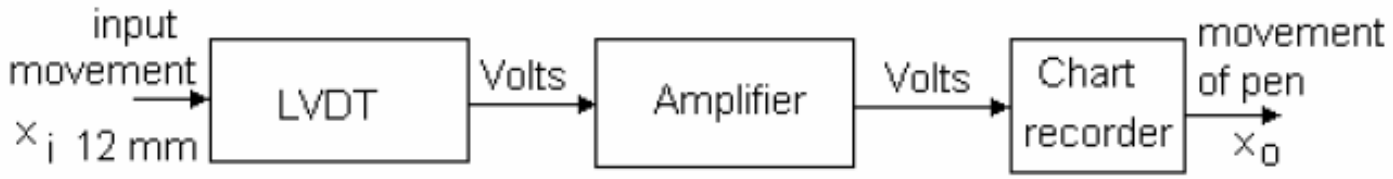
Thermocouple	3 mV per °C.
Amplifier gain	5
Meter	0.02° per mV

(Answer 54°)

Practice Example

An LVDT output is amplified and connected to a chart recorder. The block diagram is shown. Calculate the output movement of the chart recorder pen. The equations for the sub- systems are

LVDT	V = 0.2 V/mm
Amplifier	gain = 4
Chart recorder	x_o = 5 mm/V



(Answer 48 mm)

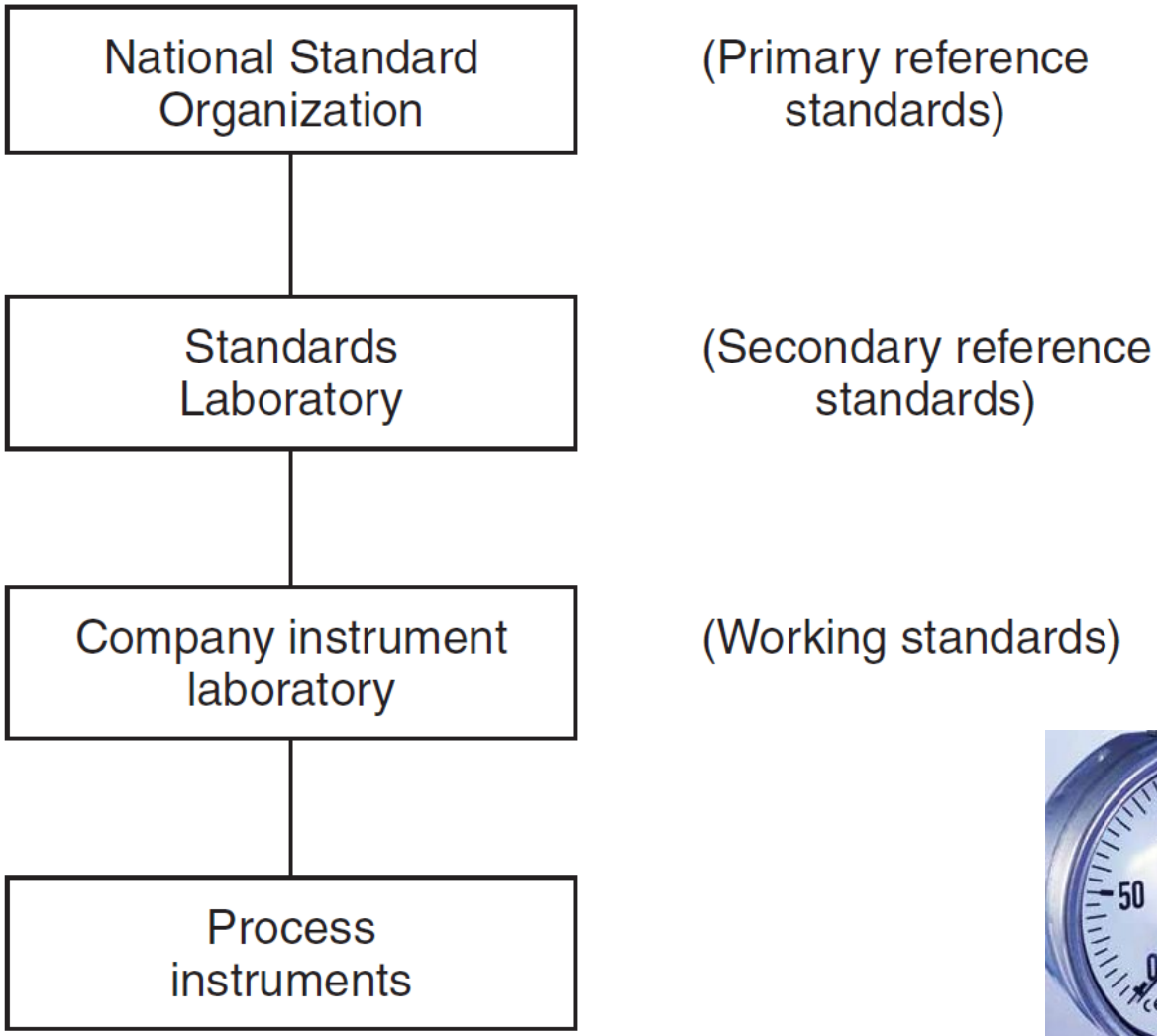
In-Situ Calibration

In-Lab Calibration

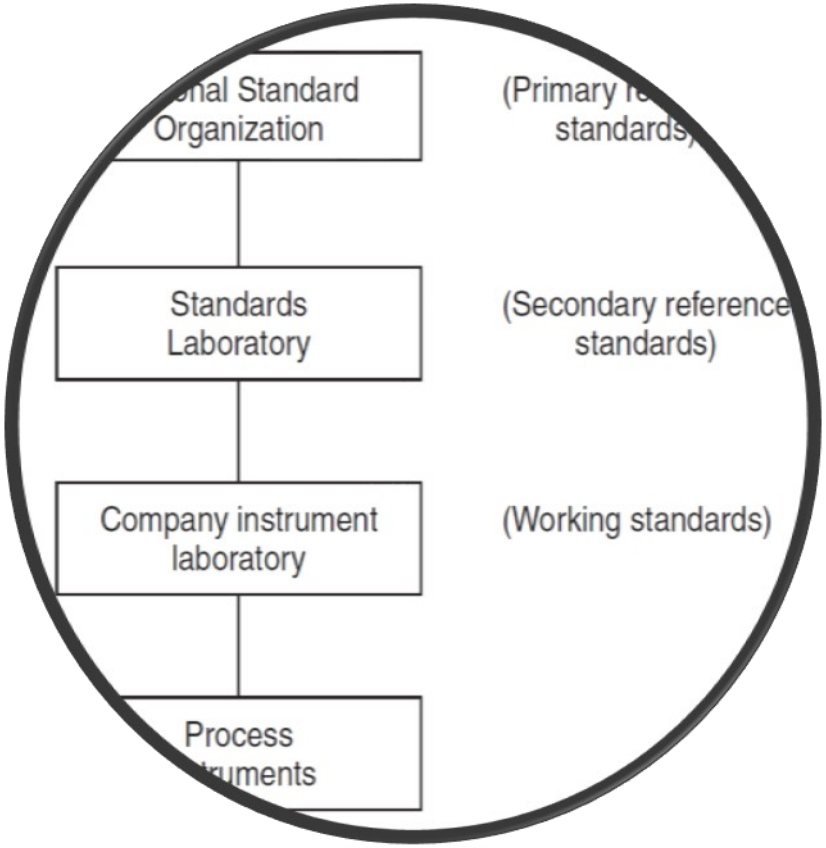
In-Lab Calibration

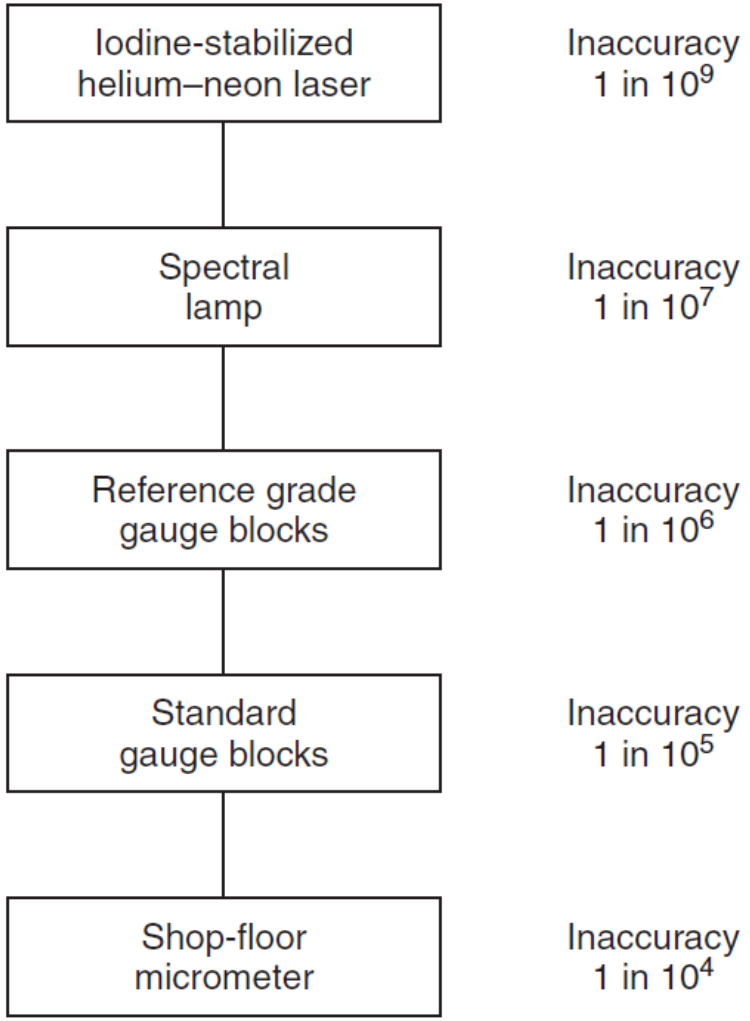
Lecture # 9-10
Calibration

Calibration chain and traceability



Calibration chain and traceability





Control of calibration environment

1. Dedicated use of instrument for calibration only
2. Environmental control
3. Compensating if calibrated
4. Proper training and procedu update/modification of calibrating staff/personnel

Calibration Record Sheet

Type of instrument:	Company serial number:
Manufacturer's part number:	Manufacturer's serial number:
Measurement limit:	Date introduced:
Location:	
Instructions for use:	
Calibration frequency:	Signature of person responsible for calibration:

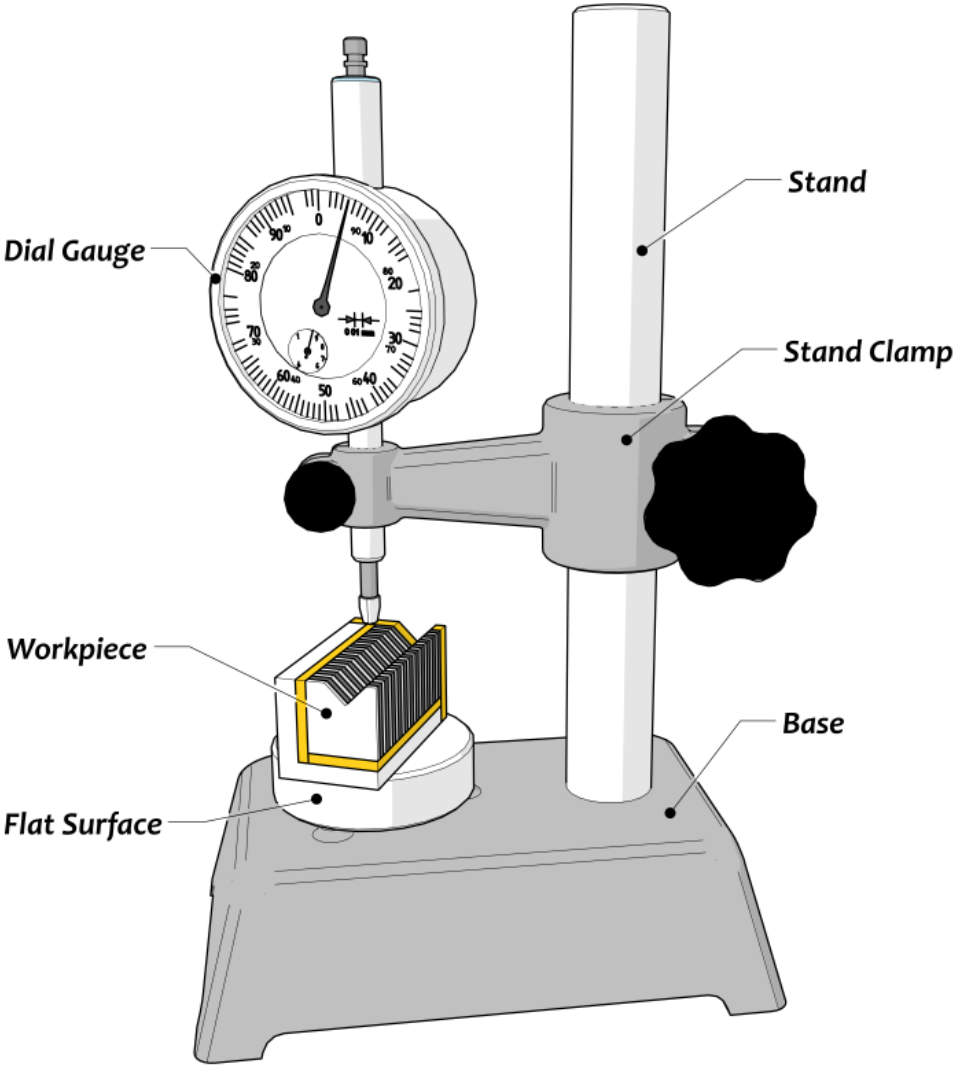
CALIBRATION RECORD

Calibration date:	Calibration results	Calibrated by

Instrument Calibration: Rationale

- Every instrument has at least one input and one output.
  - For a pressure sensor, the input would be some fluid pressure and the output would (most likely) be an electronic signal.
  - For a loop indicator, the input would be a 4-20 mA current signal and the output would be a human-readable display.
  - For a variable-speed motor drive, the input would be an electronic signal and the output would be electric power to the motor.
- Calibration and ranging are two tasks associated with establishing an accurate correspondence between any instrument's input signal and its output signal.

Dial Gauge



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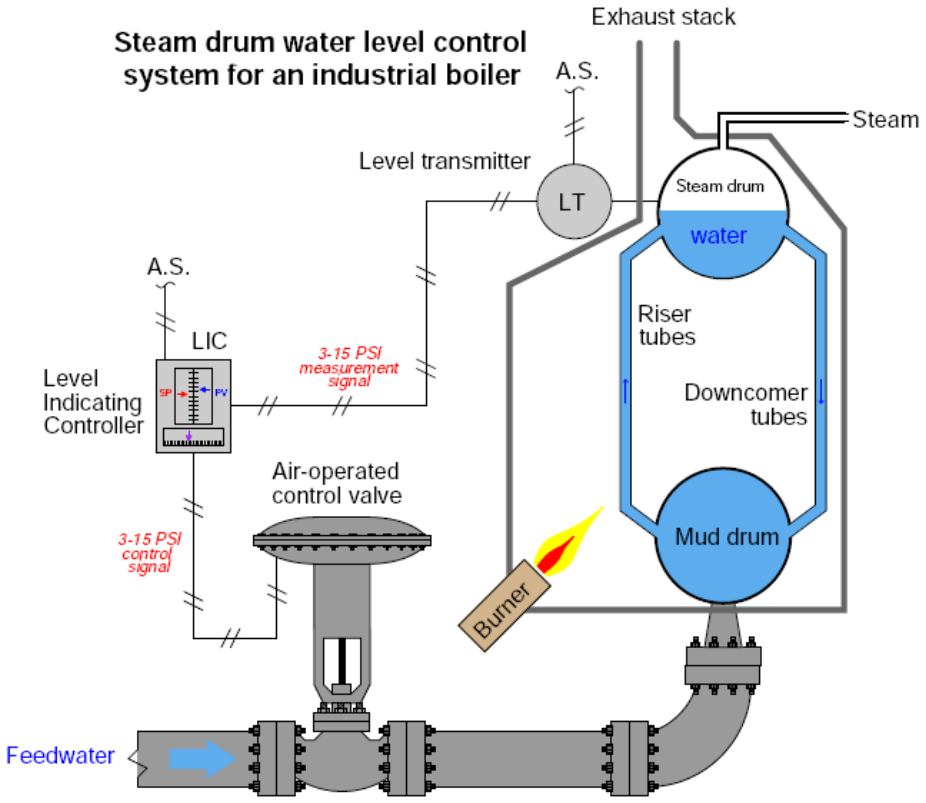
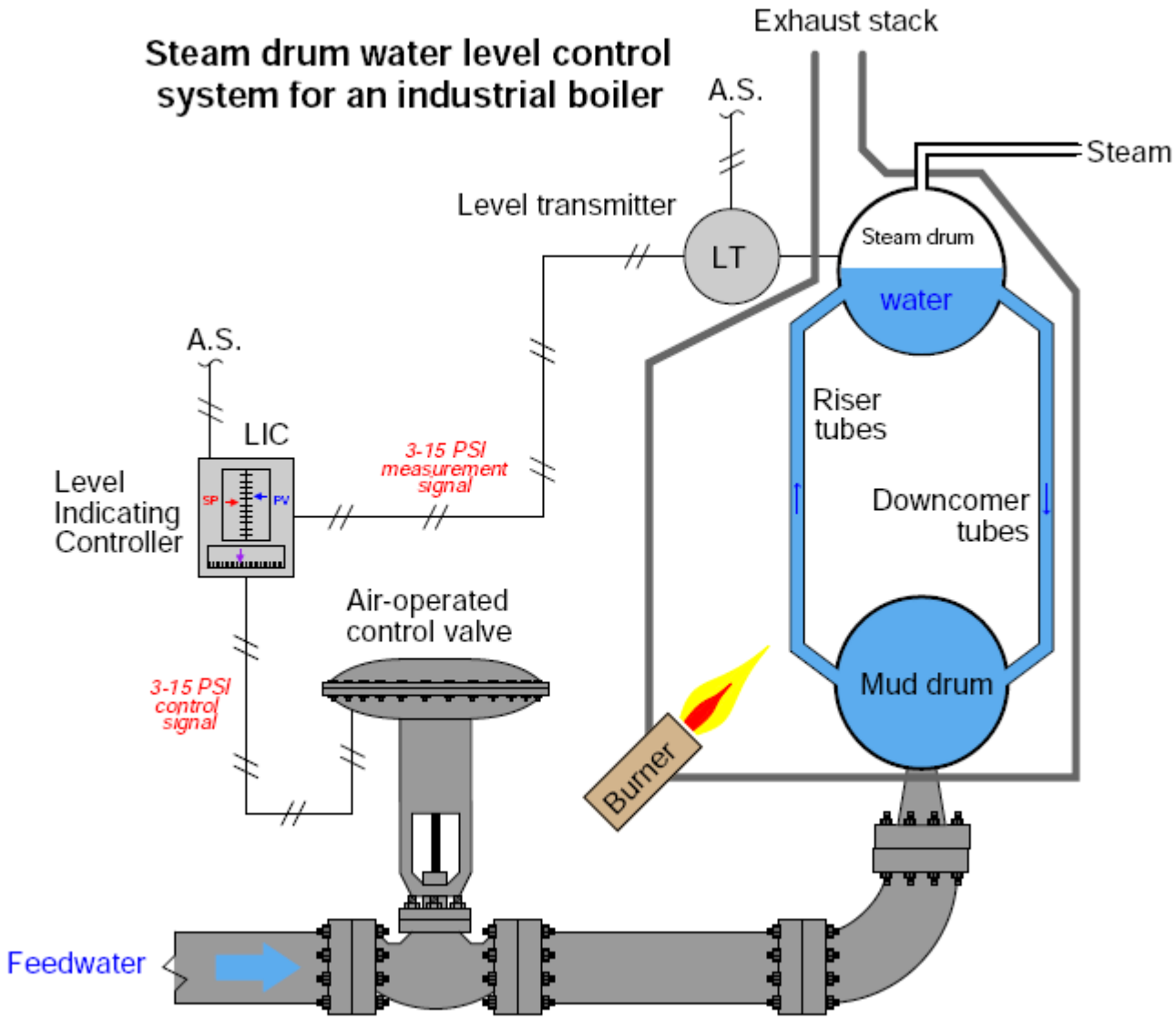
Instrument Calibration-Example



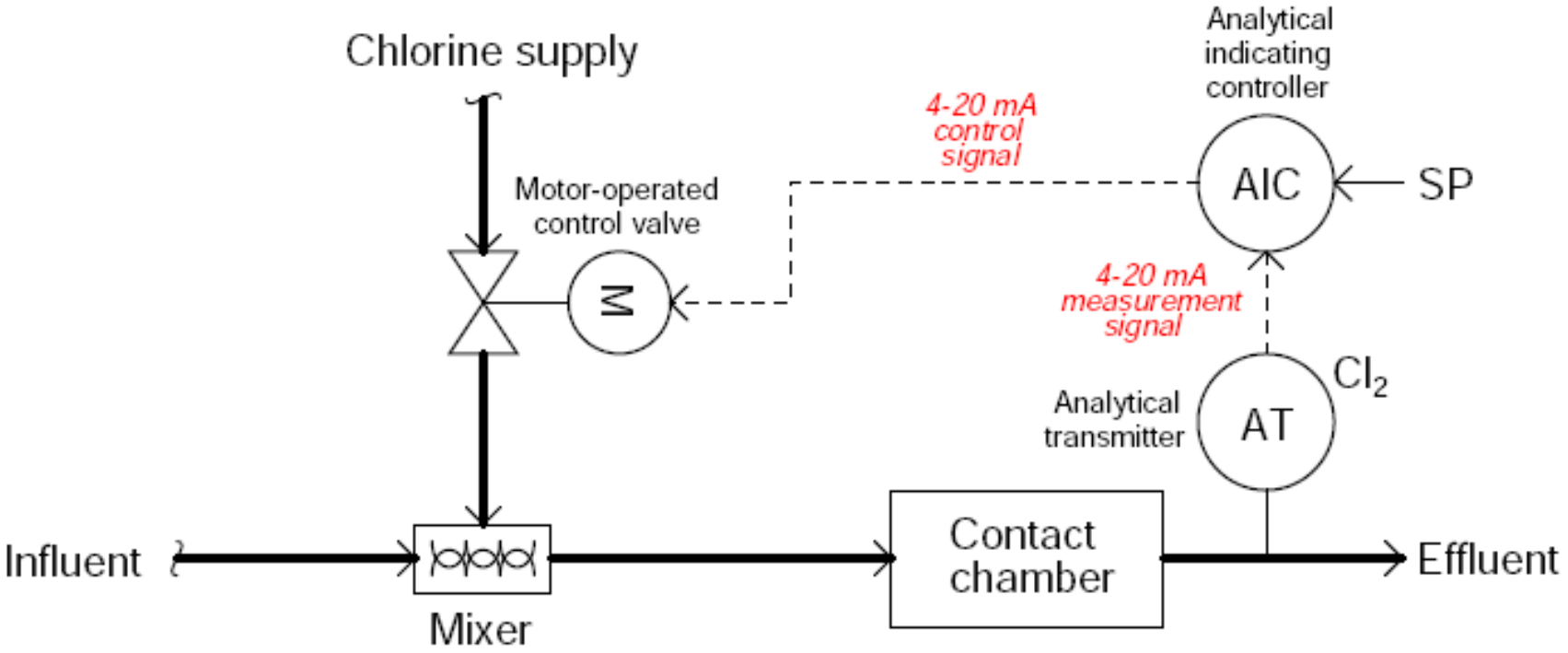
Transmitter air signal pressure	Steam drum water level
3 PSI	0% (Empty)
6 PSI	25%
9 PSI	50%
12 PSI	75%
15 PSI	100% (Full)

Controller output signal pressure	Control valve position
3 PSI	0% open (Fully shut)
6 PSI	25% open
9 PSI	50% open
12 PSI	75% open
15 PSI	100% (Fully open)

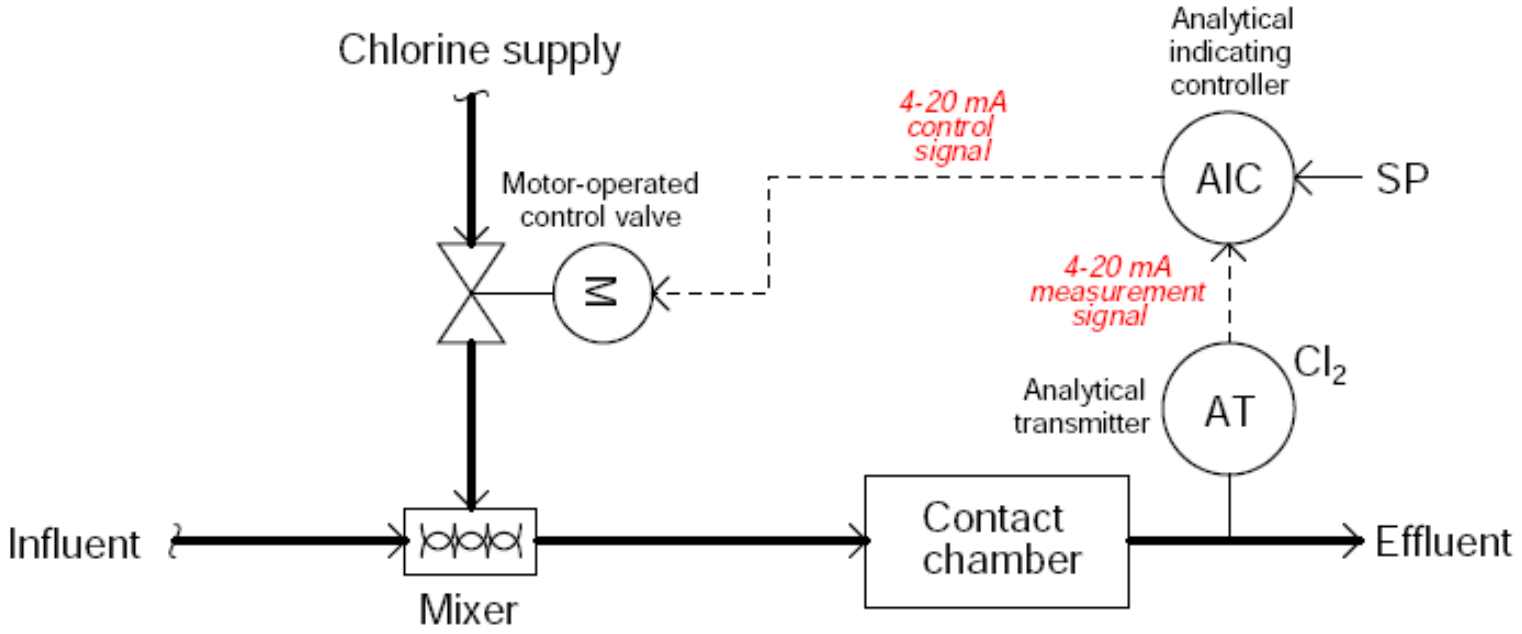
Instrument Calibration: Example



Instrument Calibration: Example 2



Instrument Calibration: Example 2



Controller output signal current	Control valve position
4 mA	0% open (Fully shut)
8 mA	25% open
12 mA	50% open
16 mA	75% open
20 mA	100% (Fully open)

Transmitter signal current	Chlorine concentration
4 mA	0% (no chlorine)
8 mA	25%
12 mA	50%
16 mA	75%
20 mA	100% (Full concentration)

Class Quiz

- A circuit requirement for a resistance of 550 is satisfied by connecting together two resistors of nominal values 220 and 330 in series. If each resistor has a tolerance of ± 2%, what is the error (absolute and in percentage) in the total resistance thus

$$e = \sqrt{(0.02 \times 220)^2 + (0.02 \times 330)^2} = 7.93$$

$$S = 550\,\Omega \pm 7.93\,\Omega \text{ or } S = 550\,(1 \pm 0.0144)\,\Omega, \qquad \text{i.e. } S = 550\,\Omega \pm 1.4\%$$

Calibration versus re-ranging

- To calibrate an instrument means to check and adjust (if necessary) its response so the output accurately corresponds to its input throughout a specified range.
- One cannot perform a true calibration without comparing an instrument's response to known, physical stimuli.
- To range an instrument means to set the lower and upper range values so it responds with the desired sensitivity to changes in input.
  - For example, a pressure transmitter set to a range of 0 to 200 PSI (0 PSI = 4 mA output ; 200 PSI = 20 mA output) could be re-ranged to respond on a scale of 0 to 150 PSI (0 PSI = 4 mA ; 150 PSI = 20 mA).

Calibration versus Re-Ranging

Transmitter air signal pressure	Steam drum water level
3 PSI	0% (Empty)
6 PSI	25%
9 PSI	50%
12 PSI	75%
15 PSI	100% (Full)

- After Re-Ranging

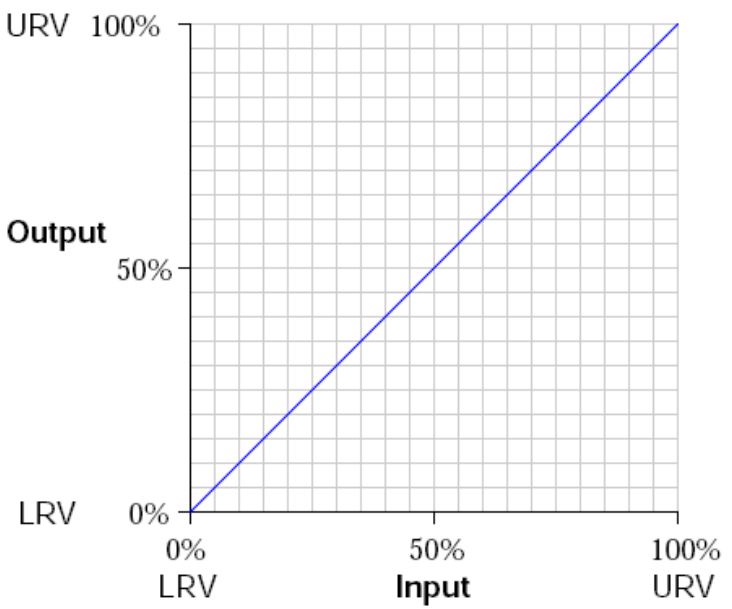
Transmitter air signal pressure	Actual steam drum water level
3 PSI	40%
6 PSI	45%
9 PSI	50%
12 PSI	55%
15 PSI	60%

Re-ranging of Analog and Digital Sensors/Instruments

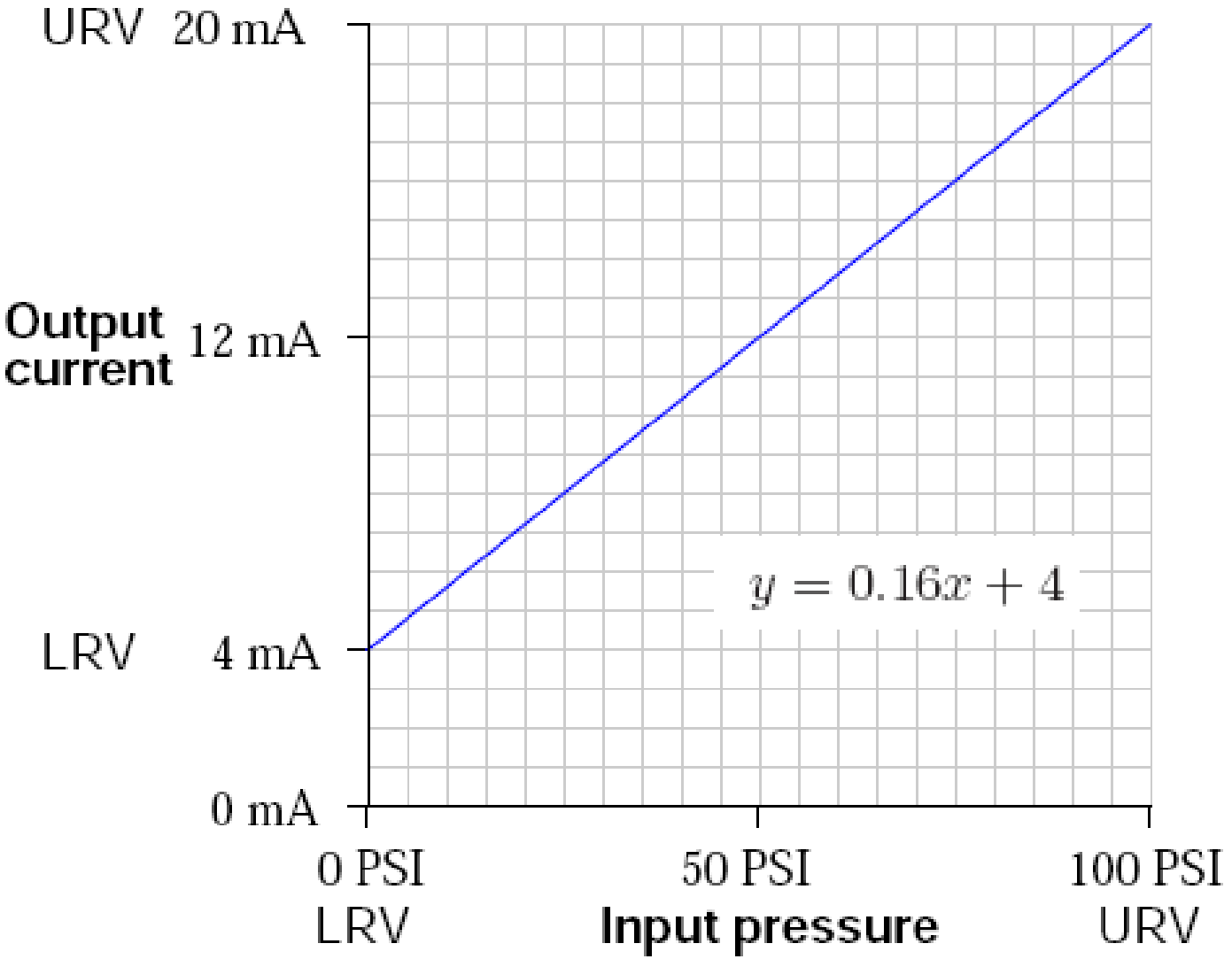
- In analog instruments, re-ranging could (usually) only be accomplished by re-calibration, since the same adjustments were used to achieve both purposes.
- In digital instruments, calibration and ranging are typically separate adjustments, i.e. it is possible to re-range a digital transmitter without having to perform a complete recalibration

Zero & Span Adjustment/Setting

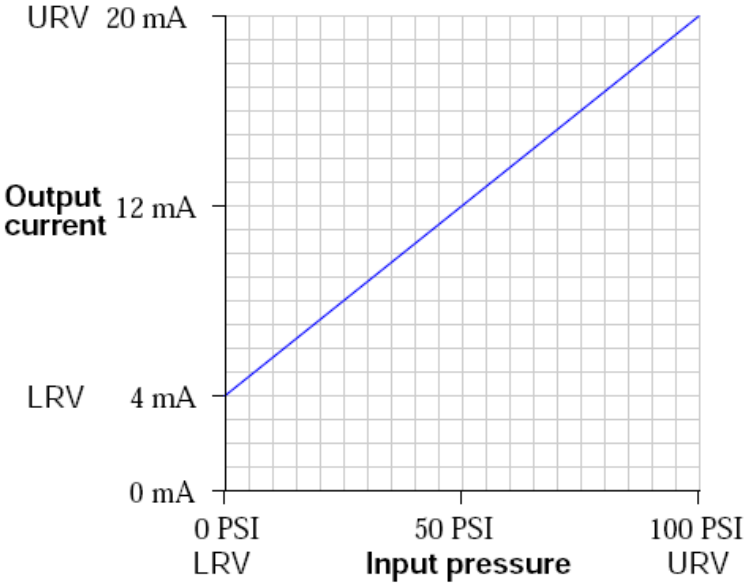
- The purpose of calibration is to ensure the input and output of an instrument correspond to one another predictably throughout the entire range of opera



Zero & Span Adjustment/Setting



Zero & Span Adjustment/Setting



$$y = 0.16x + 4$$

- A “zero” adjustment is always achieved by adding or subtracting some quantity, just like the y-intercept term b adds or subtracts to the product mx.
- A “span” adjustment is always achieved by multiplying or dividing some quantity, just like the slope m forms a product with our input variable x.

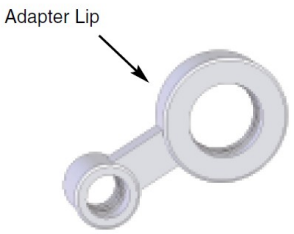
Zero & Span Adjustments

- Zero adjustments typically take one or more of the following forms in an instrument:
  - Bias force (spring or mass force applied to a mechanism)
  - Mechanical offset (adding or subtracting a certain amount of motion)
  - Bias voltage (adding or subtracting a certain amount of potential)
- Span adjustments typically take one of these forms:
  - Fulcrum position for a lever (changing the force or motion multiplication)
  - Amplifier gain (multiplying or dividing a voltage signal)
  - Spring rate (changing the force per unit distance of stretch)

Calibration: Example

Newport Medical Instruments, Inc.

NEWPORT e360 VENTILATOR



ADP2105M
Exhalation Valve Adapter

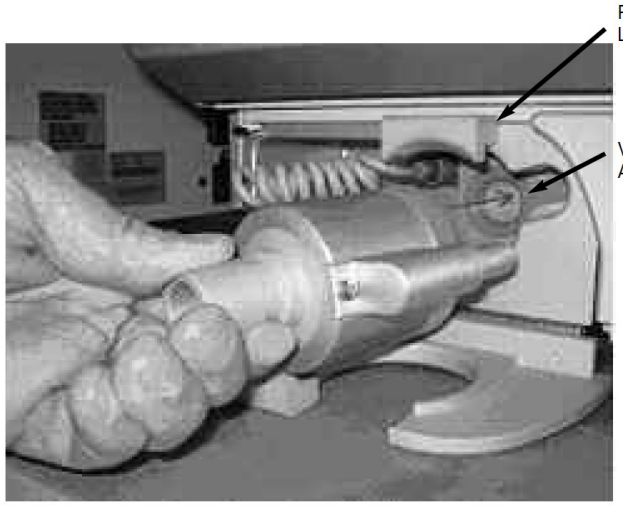


Table 5-2 Zero Offset Calibration

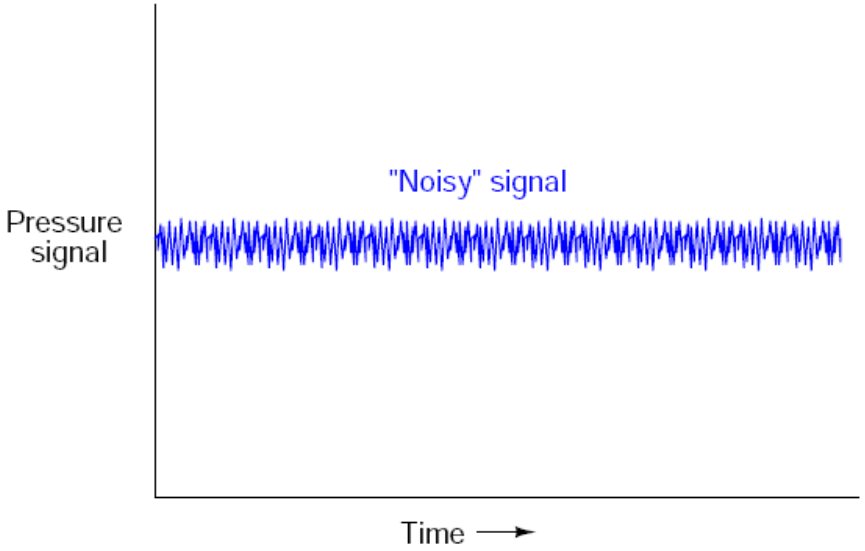
ZERO SETTING					
TRANSDUCER ID	**LCD DISPLAY**	**t Insp**	**PRESSURE**	**TOLERANCE**	**TUBE COLOR**
XD107	Drive Pressure	0	3.00 cmH_2O	±0.05	Orange
XD106	Machine 2	2	0.00 cmH_2O	±0.05	Green
XD105	Machine 1	4	0.00 cmH_2O	±0.05	Clear
XD102	Air Gas Supply	6	0.0 psig	±0.1	Yellow
XD103	O_2 Gas Supply	8	0.0 psig	±0.1	Blue

Table 5-3 Gain Calibration

GAIN SETTING						
TRANSDUCER ID	**LCD DISPLAY**	**t Insp**	**PRESSURE**	**TOLERANCE**	**DESIGN ATION**	**TUBE COLOR**
XD107	Drive Pressure	1	110 cmH_2O	±1.0	Bottom Port	Orange
XD106	Machine 2	3	110 cmH_2O	±1.0	Bottom Port	Green
XD105	Machine 1	5	110 cmH_2O	±1.0	Top Port	Clear
XD102	Air Gas Supply	7	25 psig	±0.1	Top Port	Yellow
XD103	O_2 Gas Supply	9	25 psig	±0.1	Top Port	Blue

Damping adjustments

- Imagine a pressure transmitter sensing water pressure at the outlet of a large pump. The flow of water exiting a pump tends to be extremely turbulent, and any pressure-sensing device connected to the immediate discharge port of a pump will interpret this turbulence as violent fluctuations in pressure.
- This means the pressure signal output by the transmitter will fluctuate as well, causing any indicator or control system connected to that transmitter to register a very “noisy” water pressure:

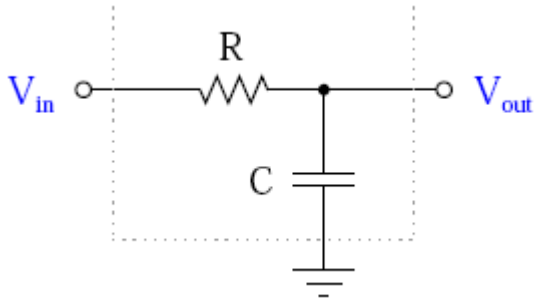


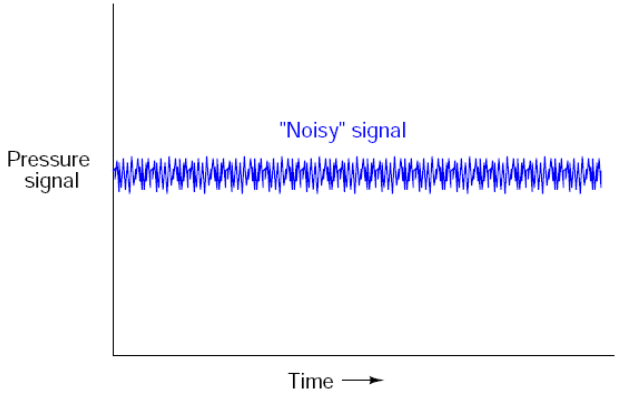
The vast majority of modern process transmitters (both analog and digital) come equipped with a feature known as damping.

This feature is essentially a low-pass filter function placed in-line with the signal, reducing the amount of process “noise” reported by the transmitter.

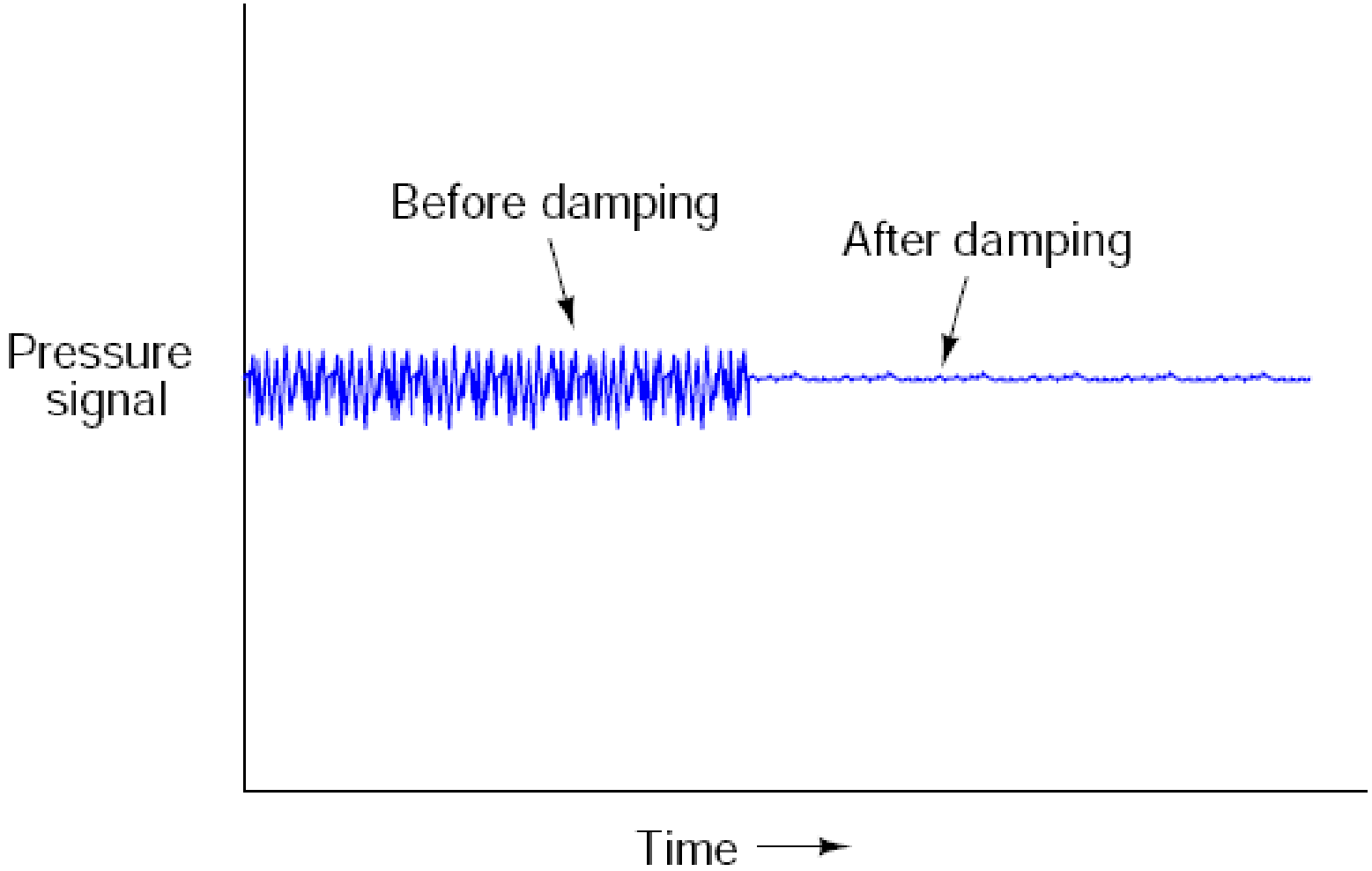
Why Low Pass Filter?

- Since this noise is of a much greater frequency than the normal cycles of pressure in a process system, it is relatively easy to reduce the amount of noise in the transmitter signal simply by filtering that electronic signal using a low-pa

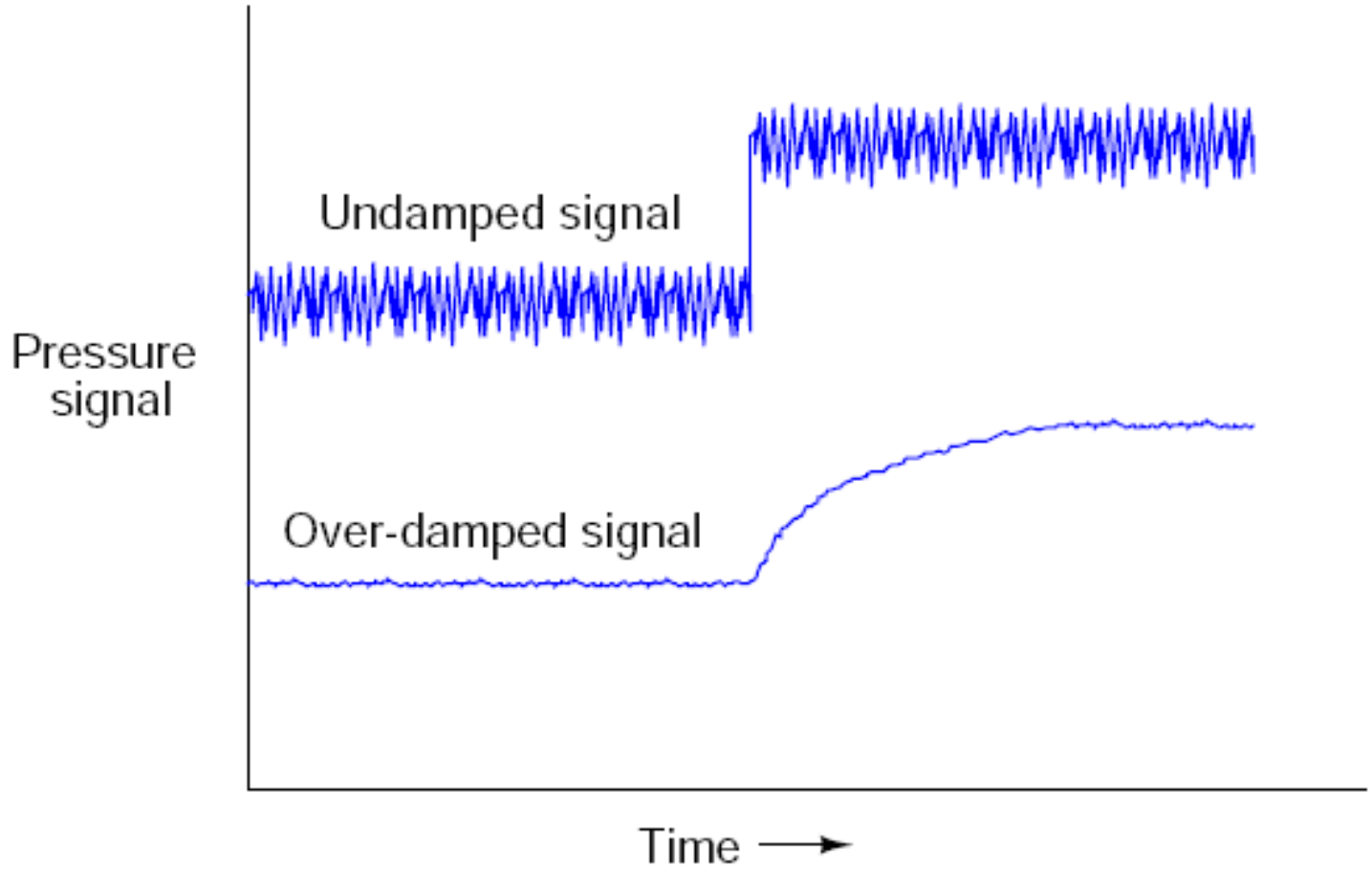




After Damping

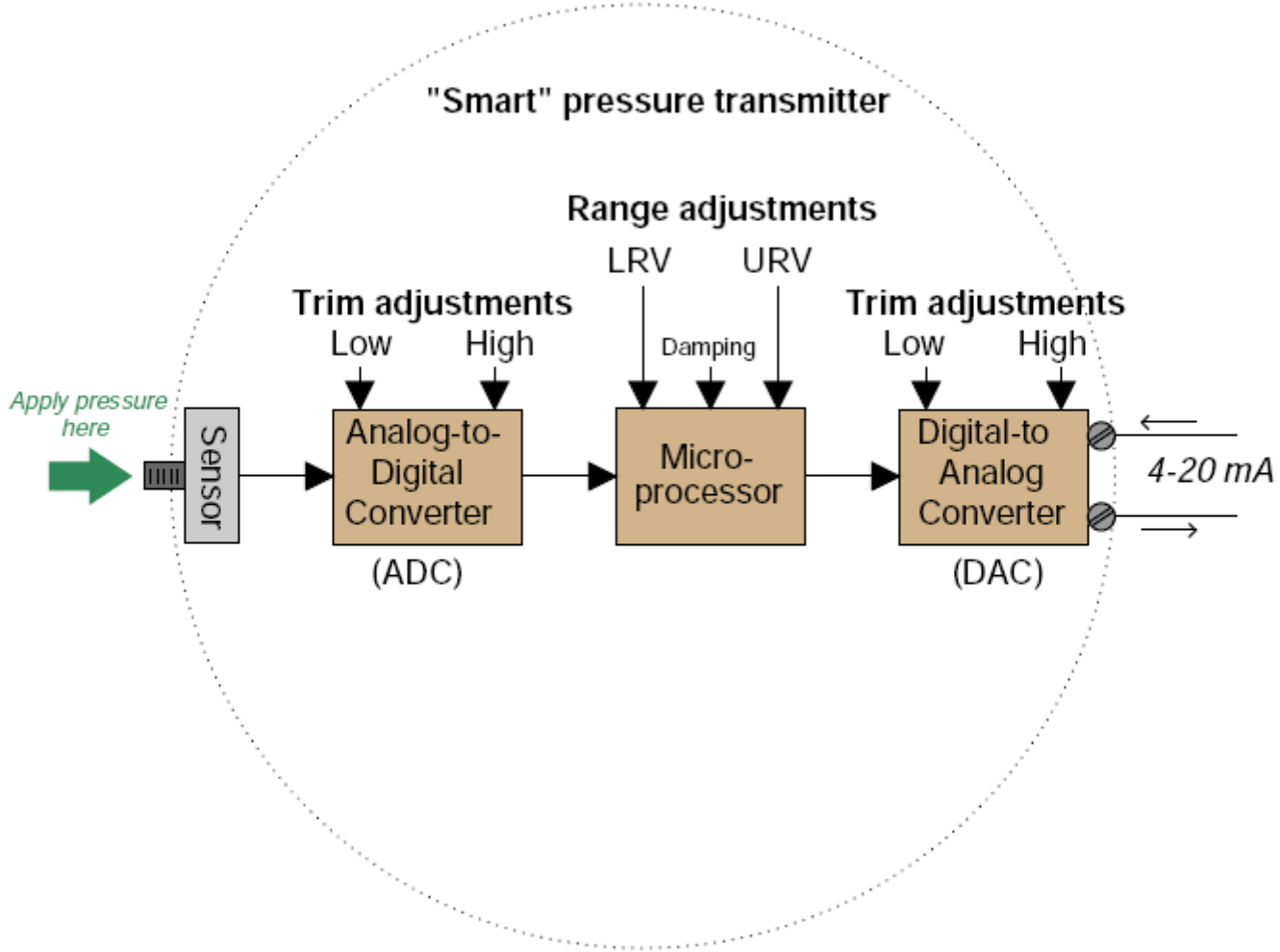


How Much Damping?

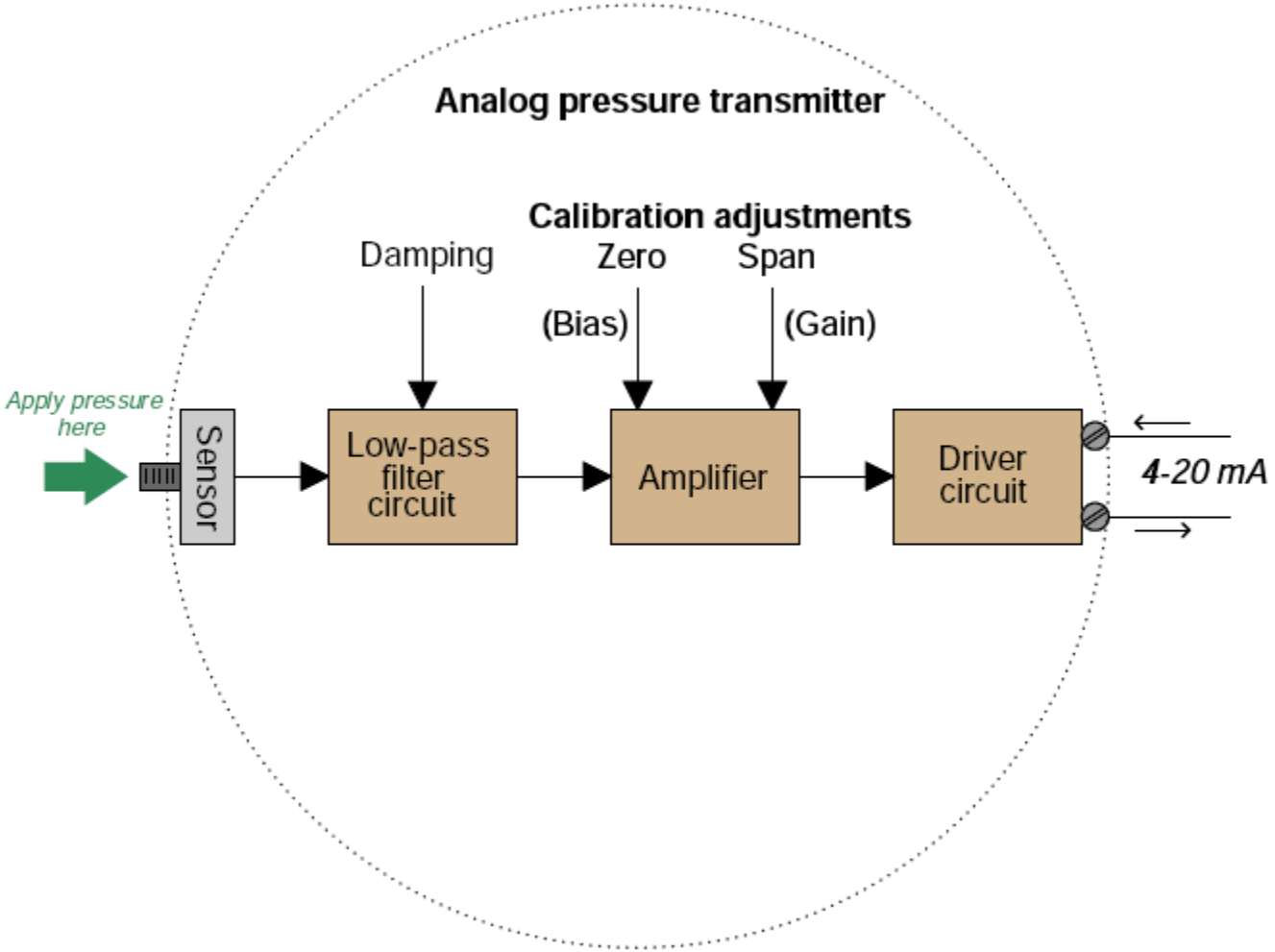


Over damping might be misleading!

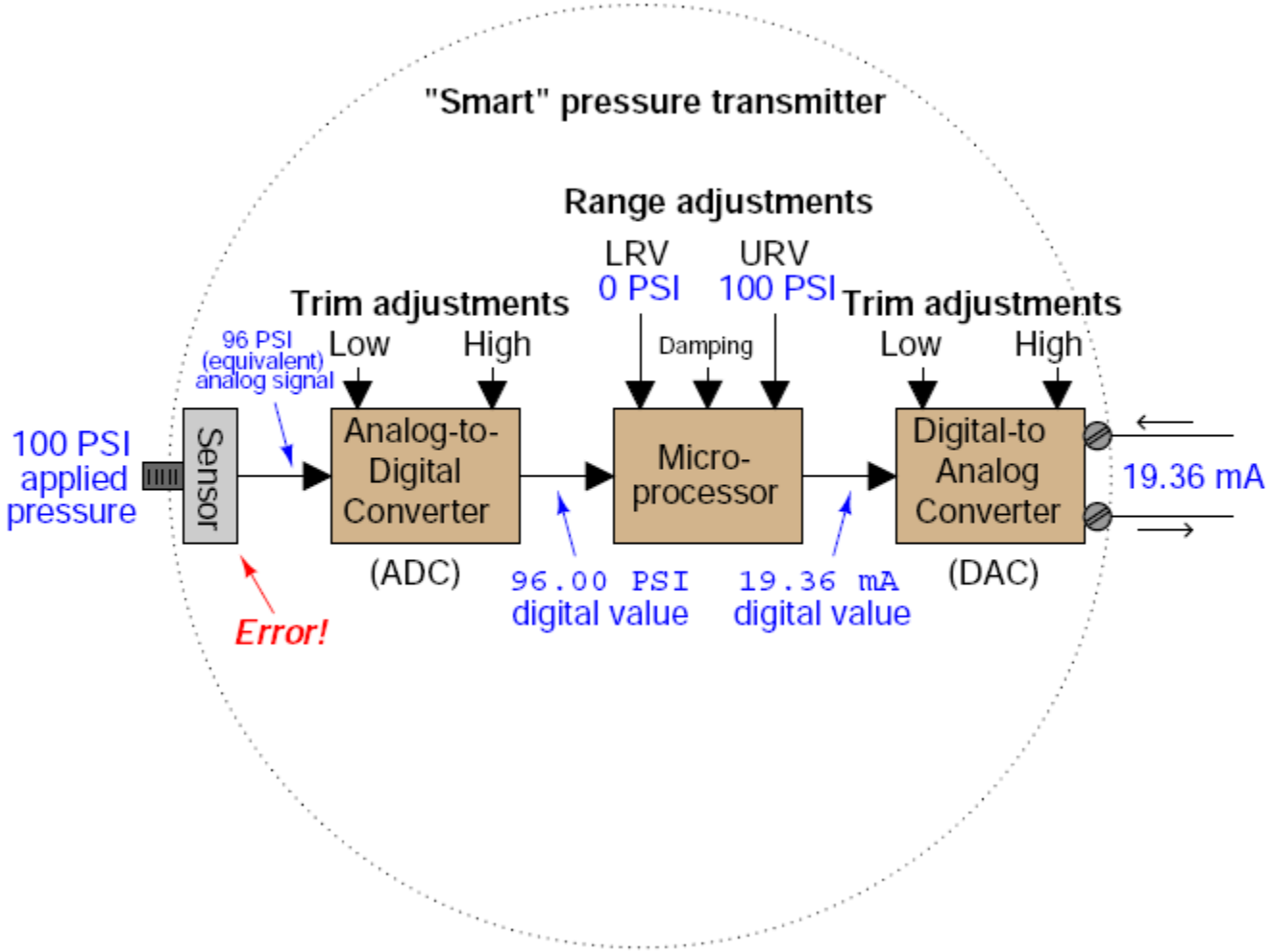
URV and LRV Settings of Digital Instruments: Digital Trim



Compared with Analog Transmitter Calibration



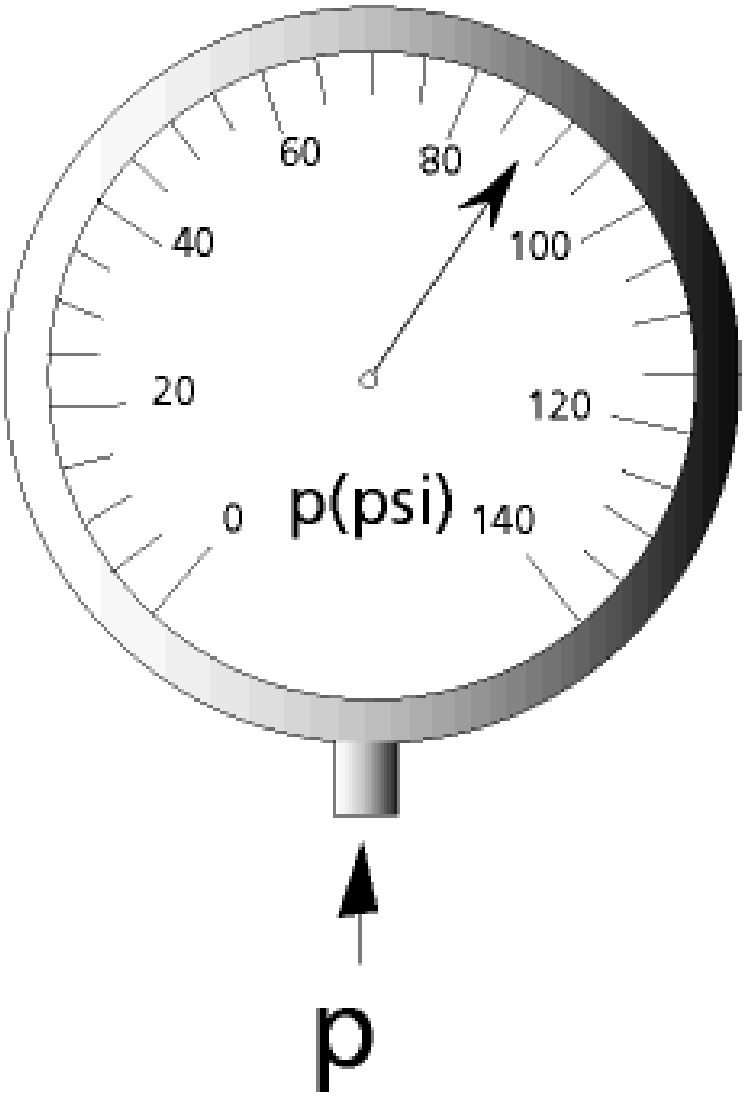
Accounting for Imperfections due to Ageing

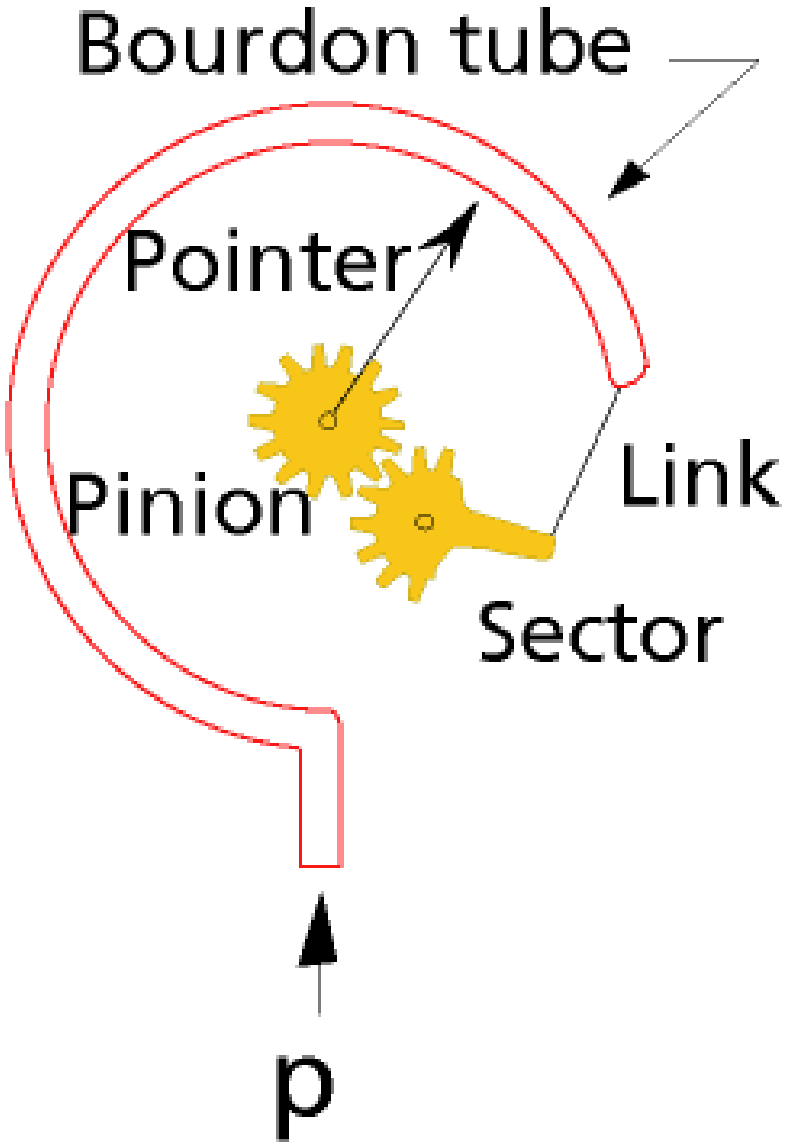


Calibration of pressure measuring instruments

0
2
4
6
8
10
EN 837-
316L
bar
CL. 1.0
WIKA

Tire Gauge


0
20
40
60
80
100
120
140
p(psi)
p


Bourdon tube
Pointer
Pinion
Link
Sector
p

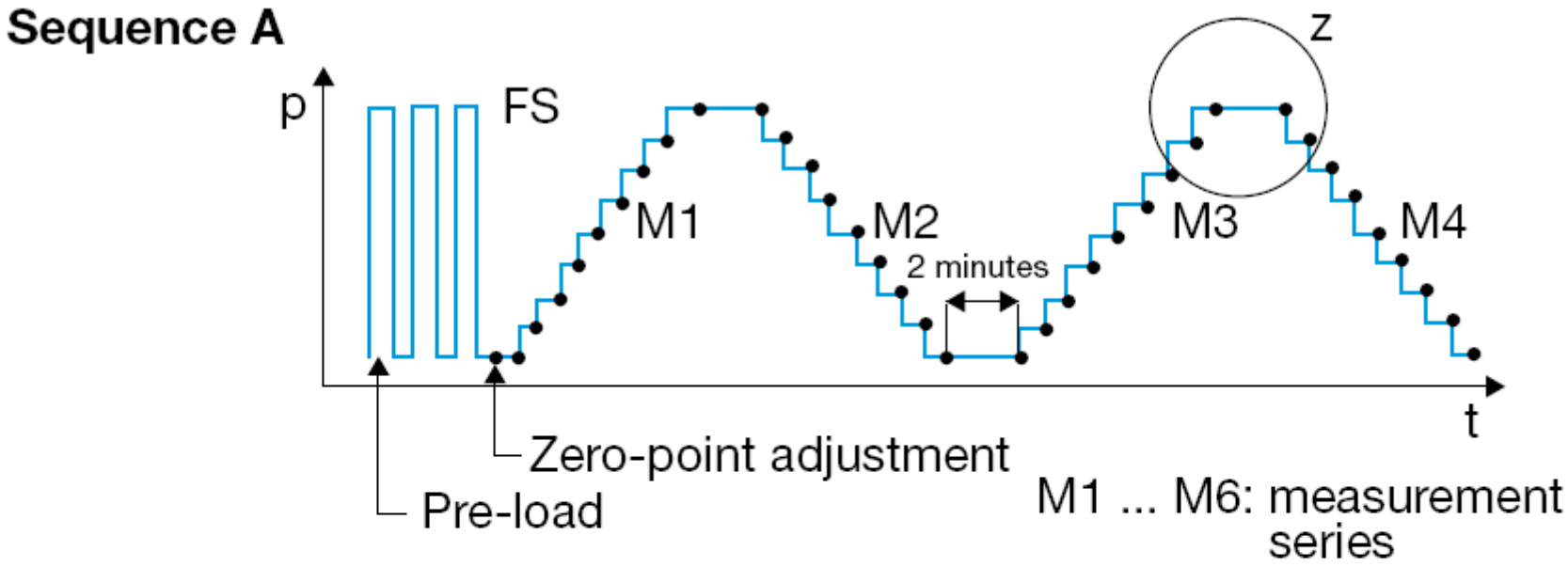
Calibration of pressure measuring instruments

Cali-bration sequence	Desired accuracy class	Number of measuring points	Number of pre-loads	Number of measurement series	
				up	down
A	< 0.1	9	3	2	2
B	0.1 to 0.6	9	2	2	1
C	> 0.6	5	1	1	1

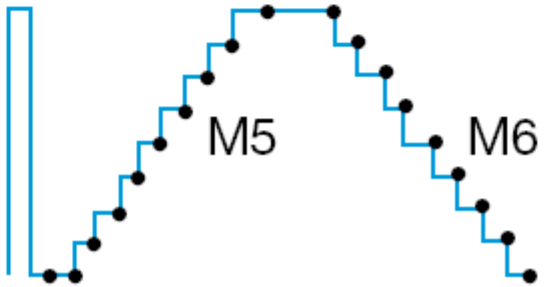
Calibration Sequence A

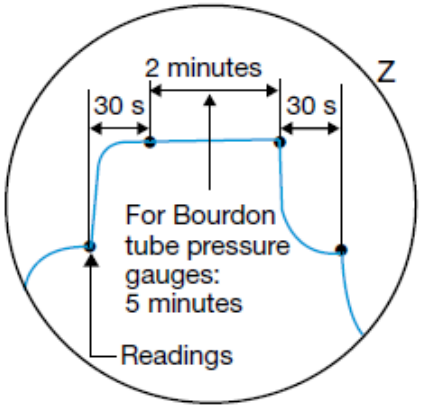
- The calibration sequence designated by A for the accuracy class < 0.1 prescribes **three** loadings up to the full scale value, to be completed prior to the actual measurement series.
- The maximum pressure is held for at least 30 seconds and is then completely released again.
- Over the course of the first measurement series, nine measuring points evenly distributed over the measuring range are measured by gradually increasing the pressure from “low to high”

Calibration Sequence A



Additional repeated measurement during 2nd setting





Calibration Sequence A

- The zero point counts as the first measuring point, but is only included in the statistical evaluation if it is free-moving, i.e. if the pointer movement is not limited by a stop pin.
- The pressure must be increased at such a low rate that the intended measuring point is not exceeded, since due to hysteresis, this could lead to a falsification of the results.
- The value reached is read after a holding time of at least 30 seconds.
- In the second measurement series, the same measuring points are measured from “top to bottom” starting with the maximum pressure.

Calibration Sequence A

- With tube pressure gauges, the housing should be given a light knock prior to reading in order to minimize friction effects on the movement.
- The final value at the last test point is also read and documented after 30 seconds.
- After two minutes at constant pressure, this value is read a second time.
- With tube pressure gauges, the maximum pressure should even be held for five minutes.

Calibration Sequence A

- In the second measurement series, the same measuring points are measured from “top to bottom” starting with the maximum pressure.
- At the end of this first measurement cycle, the zero point is measured. For this, the instrument should remain depressurized for two minutes.
- Calibration sequence A requires that the described cycle of increasing and decreasing the pressure by degrees is repeated once.

Calibration Sequence B

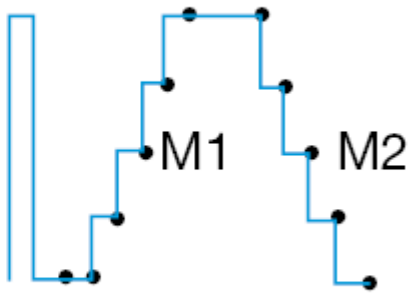
- There are only two preloads up to the maximum value, and the third measurement series ends shortly after the pressure has reached the maximum value.
- From there, the pressure is discharged immediately down to the zero value

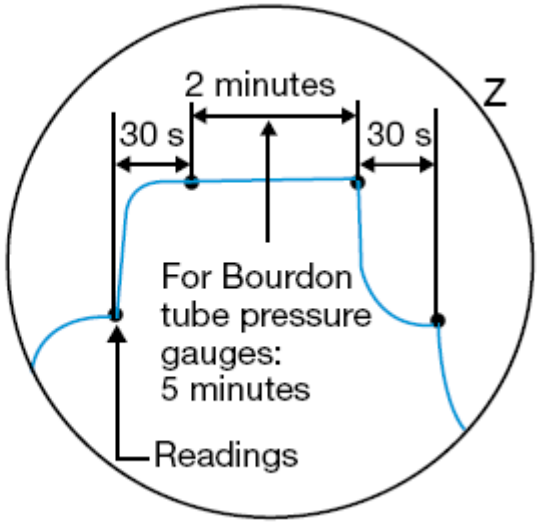
Sequence B

Calibration Sequence C

- Calibration sequence C can be applied to pressure measuring instruments of accuracy class > 0.6.
- It only requires one preload up to the maximum value and only one measurement series, which, including the zero value and the maximum value, consists of five measuring points and in which the pressure is increased by degrees and then

Sequence C

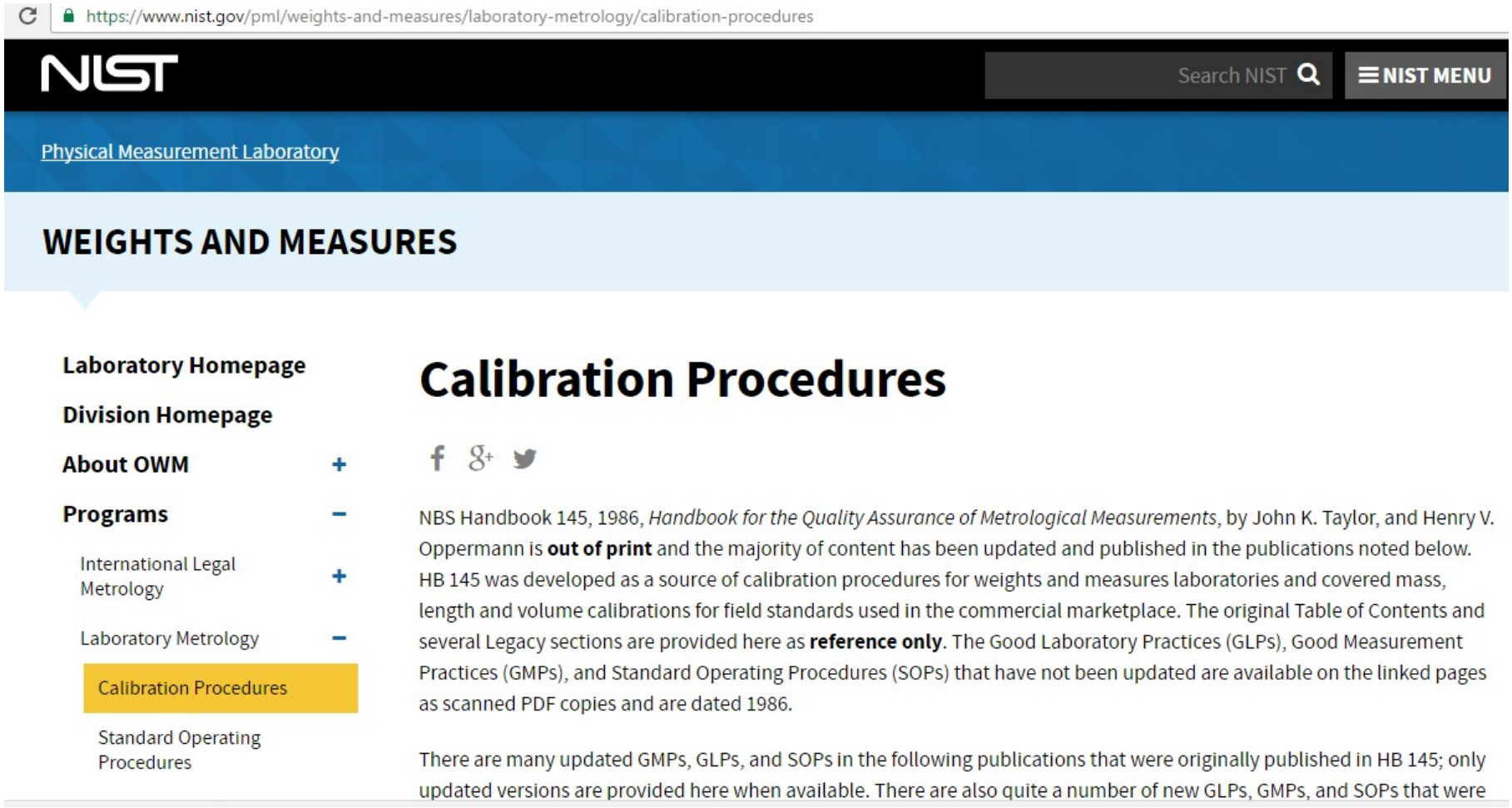




Assignment # 3

- Calibration procedures on
  - Temperature
  - Level
  - Flow
  - Chemical concentration

Useful Links for information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Calibration Procedures
NBS Handbook 145, 1986, *Handbook for the Quality Assurance of Metrological Measurements*, by John K. Taylor, and Henry V. Oppermann is **out of print** and the majority of content has been updated and published in the publications noted below. HB 145 was developed as a source of calibration procedures for weights and measures laboratories and covered mass, length and volume calibrations for field standards used in the commercial marketplace. The original Table of Contents and several Legacy sections are provided here as **reference only**. The Good Laboratory Practices (GLPs), Good Measurement Practices (GMPs), and Standard Operating Procedures (SOPs) that have not been updated are available on the linked pages as scanned PDF copies and are dated 1986.
There are many updated GMPs, GLPs, and SOPs in the following publications that were originally published in HB 145; only updated versions are provided here when available. There are also quite a number of new GLPs, GMPs, and SOPs that were

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Physical Measurement Laboratory

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The Division advances measurement science, standards, and applications for sensing optical power and thermodynamic and flow quantities to support U.S. industry and trade. We maintain the scales for two SI base units: the kelvin (temperature) and the candela (luminous intensity).

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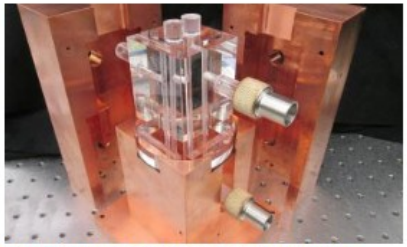
- Employment Opportunities



Realizing Pressure, Temperature, and Length using Optical Interferometry

Reflectance Measurements of Human Skin

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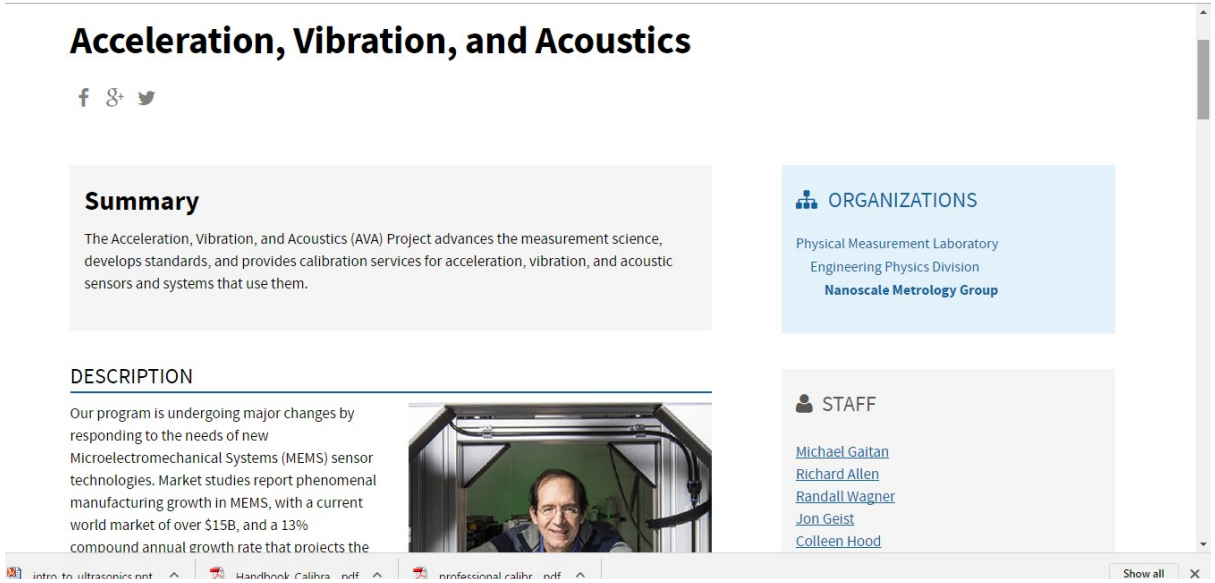
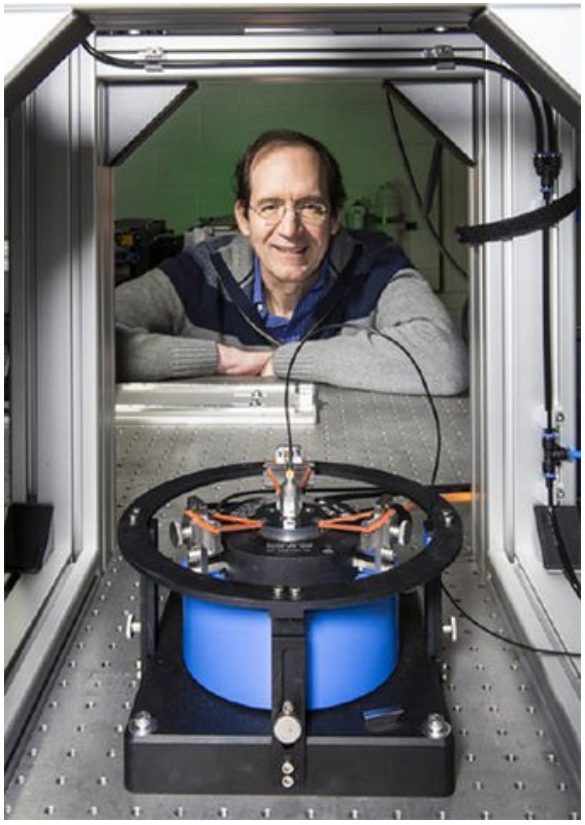

Acceleration, Vibration, and Acoustics
Summary
The Acceleration, Vibration, and Acoustics (AVA) Project advances the measurement science, develops standards, and provides calibration services for acceleration, vibration, and acoustic sensors and systems that use them.
ORGANIZATIONS
Physical Measurement Laboratory
Engineering Physics Division
Nanoscale Metrology Group
DESCRIPTION
Our program is undergoing major changes by responding to the needs of new Microelectromechanical Systems (MEMS) sensor technologies. Market studies report phenomenal manufacturing growth in MEMS, with a current world market of over $15B, and a 13% compound annual growth rate that projects the
STAFF
Michael Gaitan
Richard Allen
Randall Wagner
Jon Geist
Colleen Hood
Show all

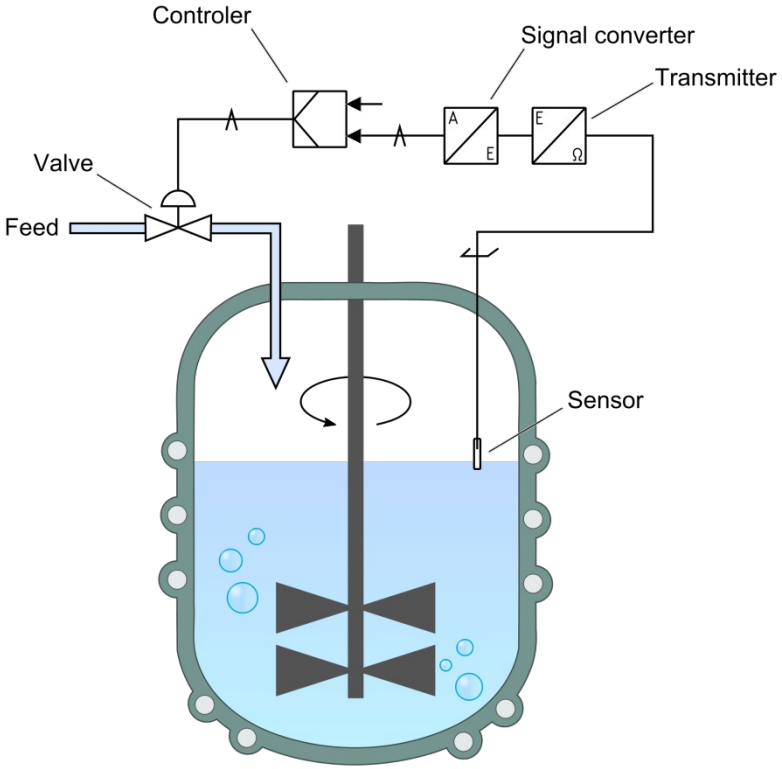


Flow Sensors

What is most important about flow measurement?

Selecting Flow Sensors

- Is the measurement for a process control application, where repeatability is the major concern, or for accounting or custody transfer, where high accuracy is important?



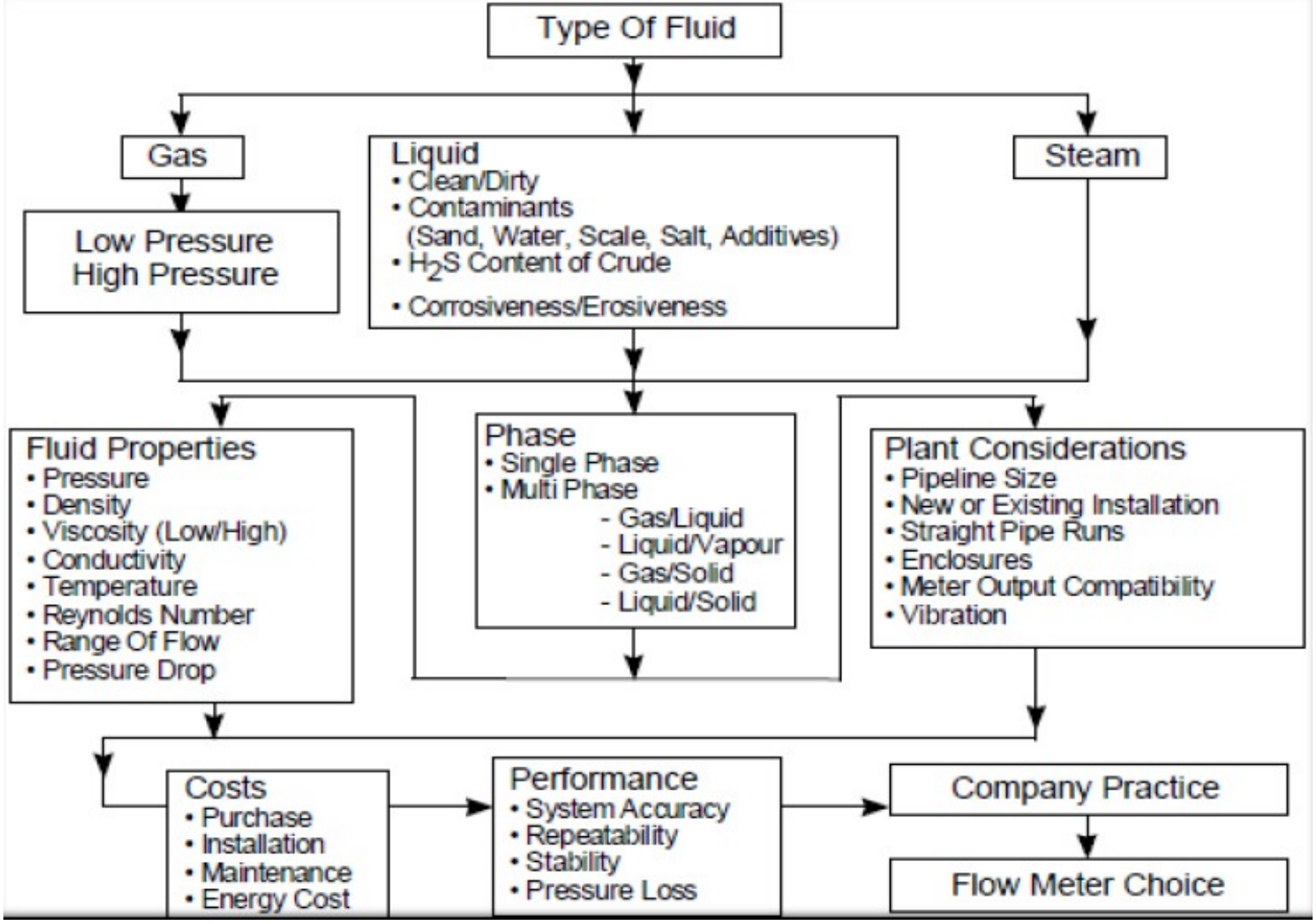
Selecting Flow Sensors

- Is the measurement for a process control application, where repeatability is the major concern, or for accounting or custody transfer, where high accuracy is important?
- Is local indication or a remote signal required? If a remote output is required, is it to be a proportional signal, or a contact closure to start or stop another device?

Selecting Flow Sensors

- Is the measurement for a process control application, where repeatability is the major concern, or for accounting or custody transfer, where high accuracy is important?
- Is local indication or a remote signal required? If a remote output is required, is it to be a proportional signal, or a contact closure to start or stop another device?
- Is the liquid to be measured clean, viscous, or a slurry?
- Is the liquid to be measured electrically conductive?
- What is the specific gravity or density of the liquid to be measured?
- What flow rates are involved in the application?
- What are the process's operating temperatures and pressures?
- What accuracy, range, linearity, repeatability, and piping requirements must be considered?

Choice of Flow Measurement System



Mass Flow Concept

- One of the fundamentals of physics is that mass is a conserved quantity.
  - It cannot be created or destroyed.
  - In the absence of sources or sinks of mass, its quantity remains constant regardless of boundaries.
  - However, if there is influx or outflow of mass through the boundaries, the sum of influx and efflux must be zero.
- Whatever ma must go out

$$\frac{dM_{in}}{dt} = \frac{dM_{out}}{dt}$$

Flow Measurement (contd.)

- A good method for measuring flow would be by somehow marking the flowing medium and detecting the movement of the mark (e.g. dye)
- In medicine, a dye dilution method of flow measurement is used for studies in hemodynamic
- However, placing any foreign material into the flowing medium may be either impractical or forbidden for some other reasons

Flow Measurement (contd.)

- An alternative would be to change some physical properties of the moving medium
- The best physical property that can be easily modified without causing undesirable effects is

Temperature

Anemometers

Thermal Anemometers

- The amount of heat removed from a heated temperature sensor by a flowing fluid can be related to that fluid's velocity
- Commonly applied to air velocities from 50 to 12,000 feet per minute
- Better at low airflow measurements than differential pressure types

Thermal Anemometers

- For measurements of turbulence levels in wind tunnels, flow patterns around models, and blade wakes in radial compressors.
- The key element of this sensor is a heated wire having typical dimensions 0.00015–0.0002 in. (0.0038–0.005 mm) in diameter and 0.040–0.080 in. (1.0–2.0 mm) in length
- Warming up the wire by electric current to 200–300C, well above the flowing media temperature and then measuring temperature of the wire.
- Makes the sensor little sensitive to the media temperature and thus no media temperature compensation is required.
- Under the no-flow condition, temperature of the wire will be constant, but when the media flows the wire will be cooled.
- The stronger the flow the stronger is the cooling.
- The advantage of the hot wire and hot film probes is in their fast speed responses; they can resolve frequencies up to 500 Hz.

Thermal Anemometers

- Two methods to control temperature and measuring the cooling effect:
  - a constant voltage and
  - a constant temperature
- Constant Voltage Method: reduction in the wire temperature is measured
- Constant Temperature Method: temperature is maintained constant at any reasonable flow rate by the increase in supplied electric power. That power is the measure of the flow rate

Thermal Anemometers

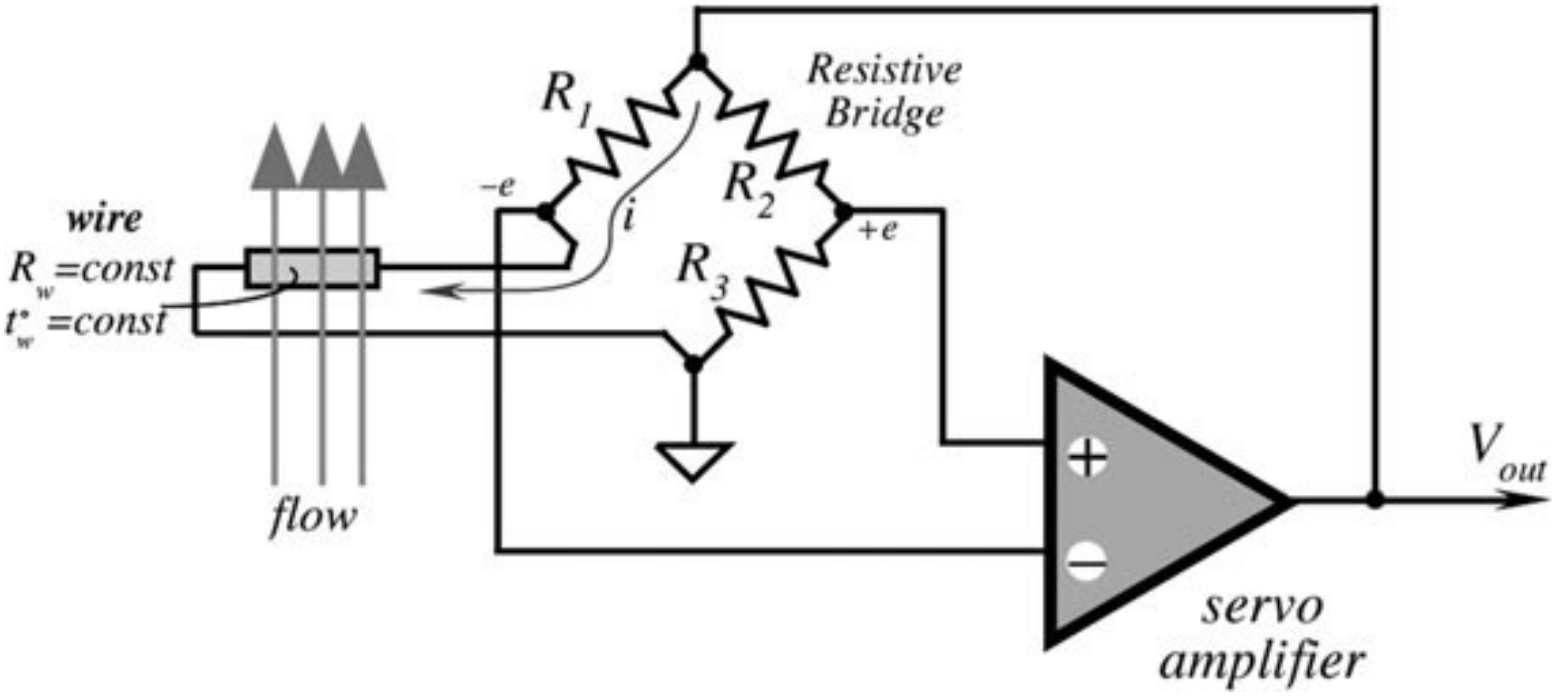
- In a hot-wire anemometer, the wire has a positive temperature coefficient and thus is used for a dual purpose:
  - to elevate temperature above the media temperature (so it will be a cooling effect) and
  - also to measure that temperature because the wire resistance goes down when the wire cools

Thermal Anemometers

- Considering the heating current *i*, the wire temperature t_w, temperature of the fluid t_f, the wire surface area A_w, and the heat transfer coefficient h, we can write the balance equation

$$i^2 R_w = h A_w (t_w - t_f)$$

Null-balanced bridge for a constant temperature hot-wire anemometer



Hot Wire & Film Probe Anemometer

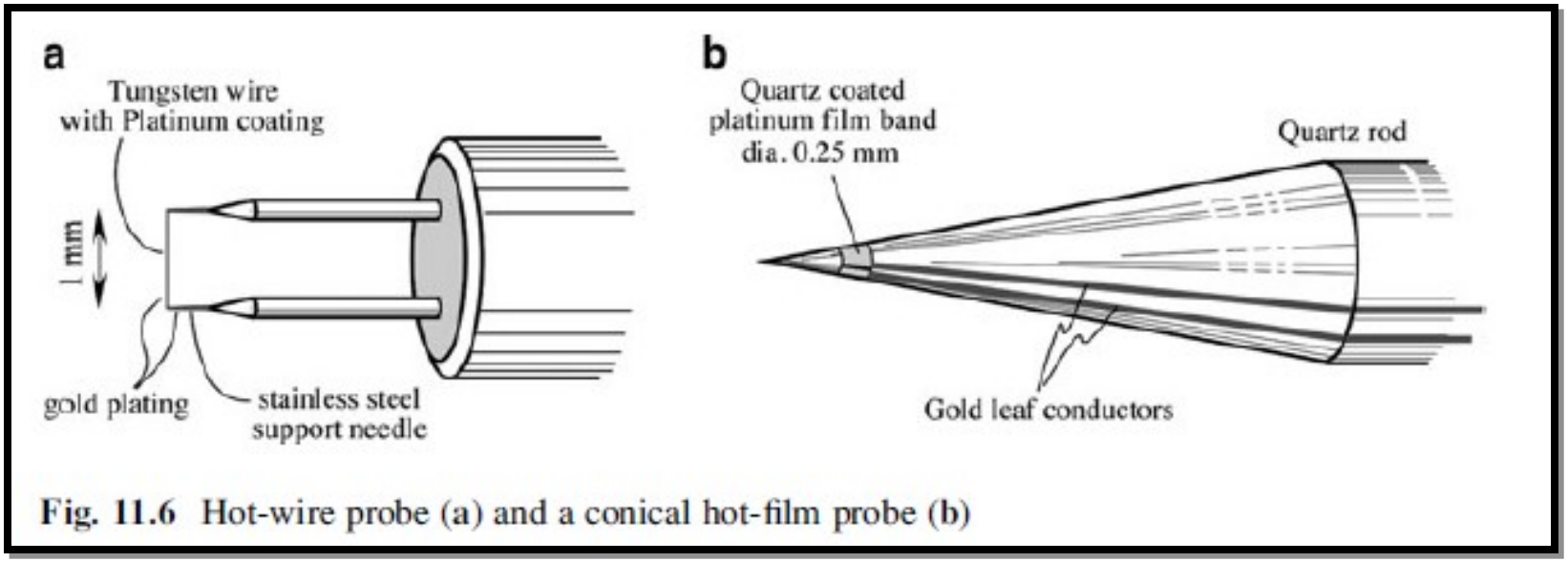


Fig. 11.6 Hot-wire probe (a) and a conical hot-film probe (b)

Advantages of Hot Film Sensors

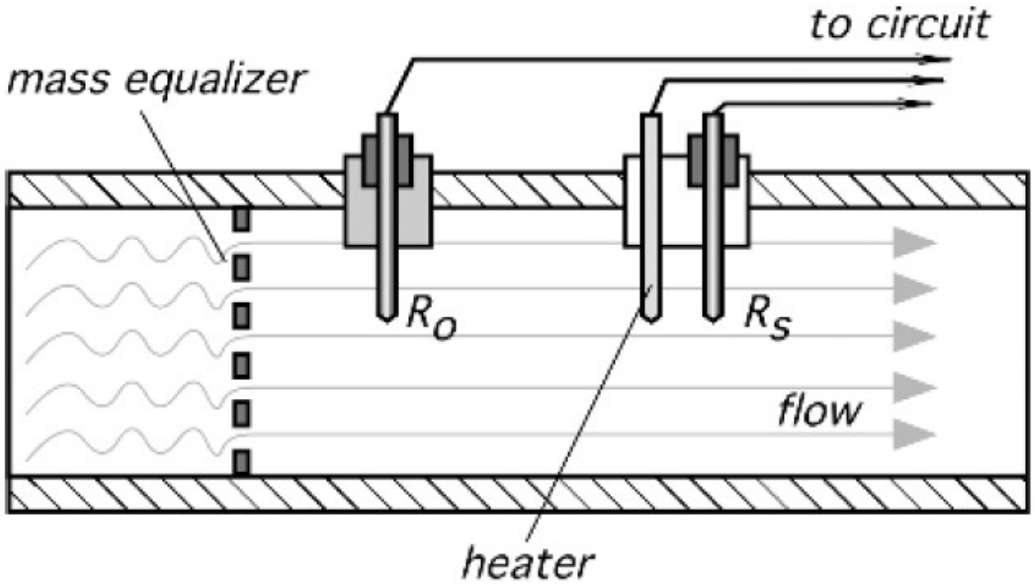
- Better frequency response (when electronically controlled) than a hot wire of the same diameter because the sensitive part of the film sensor has a larger surface area
- Lower heat conduction to the supports for a given length to diameter ratio due to the low thermal conductivity of the substrate material.
- A shorter sensing length can thus be used
- More flexibility in sensor configuration. Wedge, conical, parabolic, and flat surface shapes are available
- Less susceptible to fouling and easier to clean. A thin quartz coating on the surface resists accumulation of foreign material

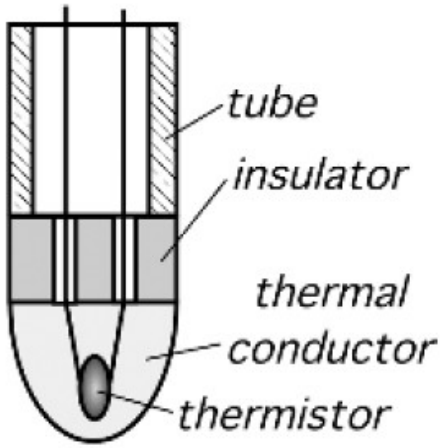
Advantages of Hot Film Sensors

- The metal film thickness on a typical film sensor is less than 1,000 A ° , thus the physical strength and the effective thermal conductivity is determined almost entirely by the substrate material.
- Most films are made of platinum due to its good oxidation resistance and the resulting long-term stability.
- A better ruggedness and stability of film sensors have led to their use for many measurements that have previously been very difficult with the more fragile and less stable hot wires.
- The hot film probes have been made on cones, cylinders, wedges, parabolas, hemispheres, and flat surfaces

Flow Measurement (contd.)

- Three-Part Thermo-anemometer





Three-Part Thermo-anemometer

- The first temperature detector R_0 *measures the temperature of the flowing medium. The heater warms up the* medium and the elevated temperature is measured by the second temperature detector R_s .
- *In a still medium, heat would be dissipated from the heater through media to both* detectors.
- In a medium with a zero flow, heat moves out from the heater mainly by thermal conduction and gravitational convection.

Three-Part Thermo-anemometer

- The higher the rate of flow, the higher the heat dissipation and the lower the temperature that will be registered by the R_s *detector.*
- *Heat loss is measured and converted into the flow rate* of the medium.

- King’s Law

Three-Part Thermo-anemometer

$$\Delta Q = kl\left(1+\sqrt{\frac{2\pi\rho c\,dv}{k}}\right)(T_s - T_0)$$

- where *k and c are the thermal conductivity and specific heat of a medium at a given* pressure, *ρ is the density of the medium, l and d are the length and diameter of the* sensor, respectively, T_s *is the surface temperature of the sensor,* T_0 *is the temperature* of the medium away from the sensor, and *v is the velocity of the medium*

Three-Part Thermo-anemometer

- Collis and Williams experimentally proved that King's theoretical law needs some correction.
- For a cylindrical sensor with

  $l/d \gg 1$

  a modified King's equation yields the velocity of the medium

$$\Delta Q = kl\left(1+\sqrt{\frac{2\pi\rho c\, dv}{k}}\right)(T_s - T_0)$$

b

$$v = \frac{K}{\rho}\left(\frac{dQ}{dt}\frac{1}{T_s - T_0}\right)^{1.87}$$

Three-Part Thermo-anemometer

$$v = \frac{K}{\rho}\left(\frac{dQ}{dt}\frac{1}{T_s - T_0}\right)^{1.87}$$

$$W = \frac{dQ}{dt}$$

$$W = \frac{e^2}{R_s}.$$

$$v_{2a} = \frac{K}{\rho}\left(\frac{e^2}{R_s}\frac{1}{T_s - T_0}\right)^{1.87}$$

Three-Part Thermo-anemometer

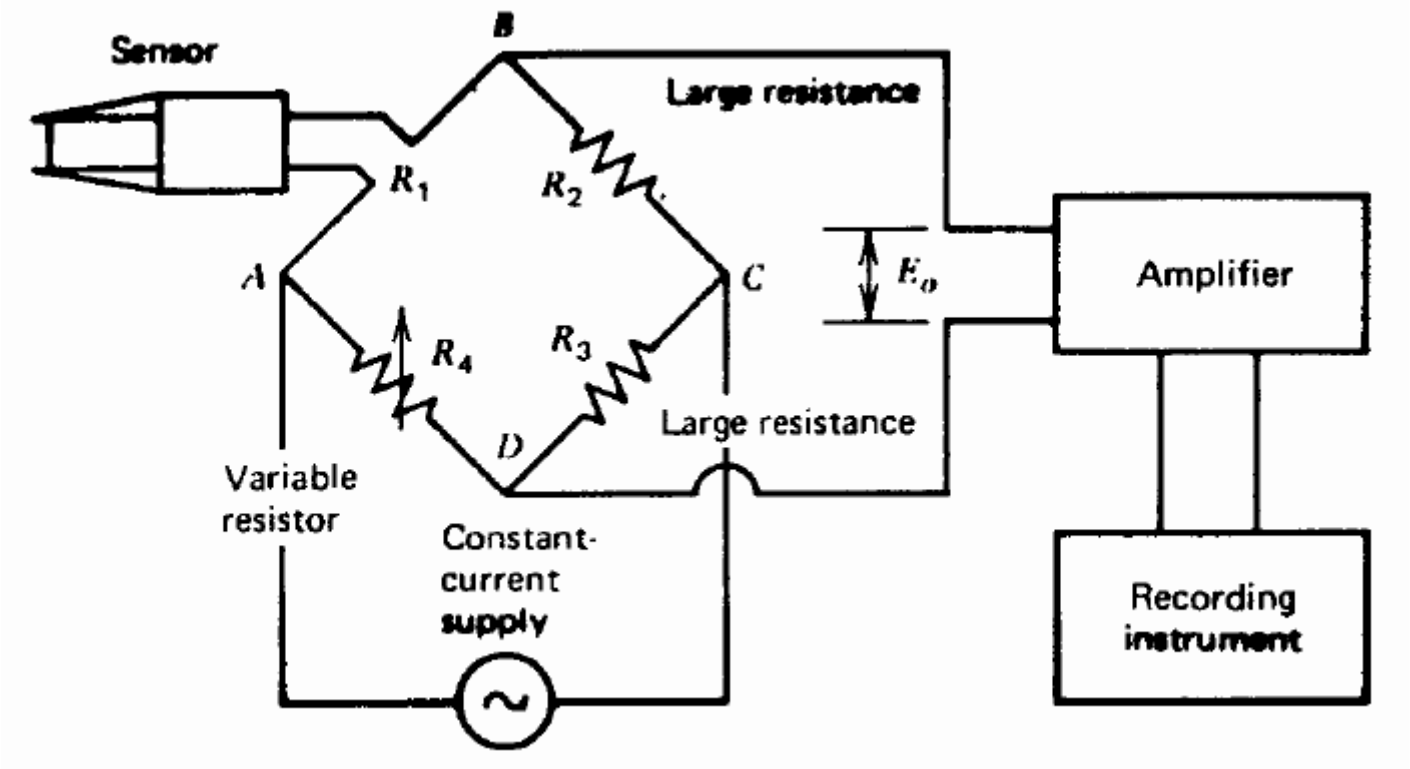
- The equation suggests that two methods of measurement are possible. In the first method, the voltage and resistance of a heating element is maintained constant.

  Whereas the temperature differential $(T_s - T_0)$ *is used as the output signal.*

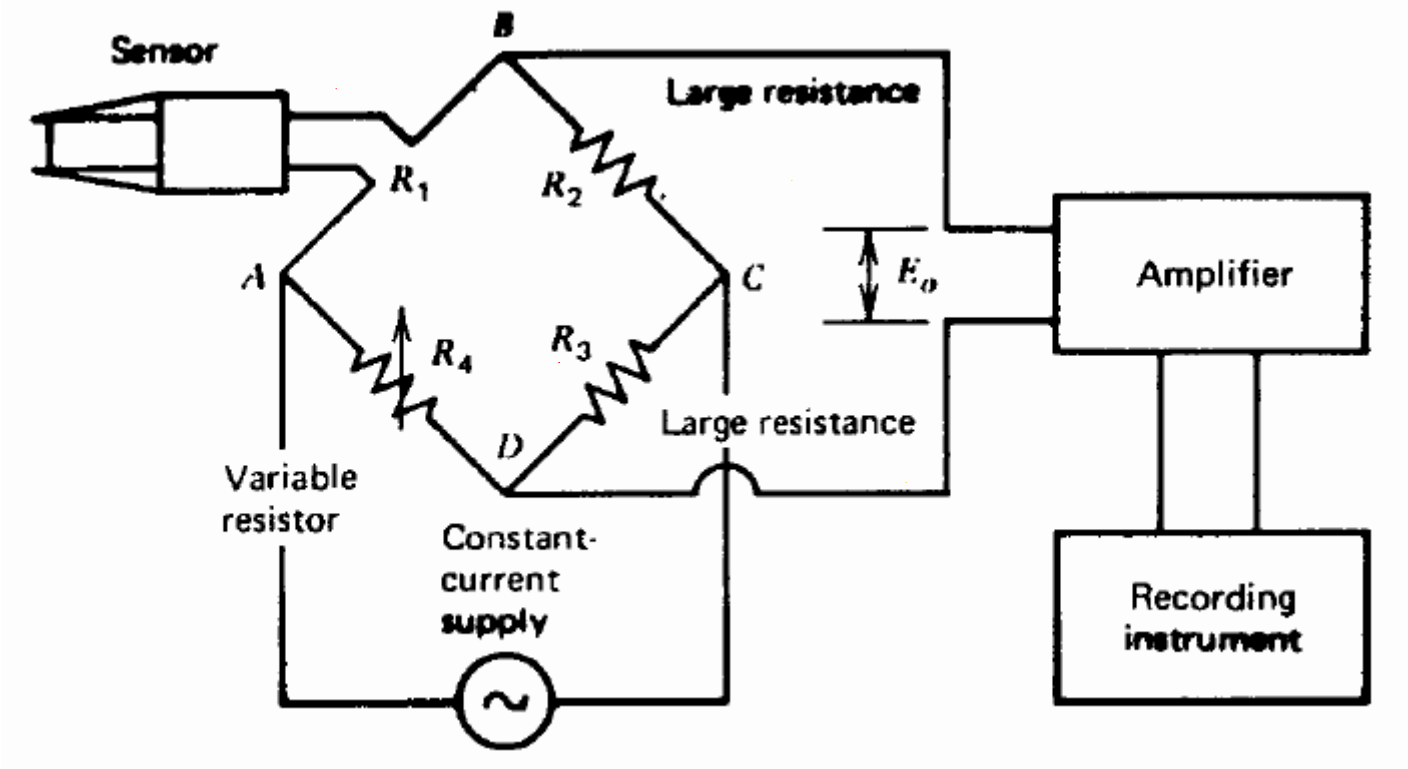
$$v_{2a} = \frac{K}{\rho}\left(\frac{e^2}{R_s}\frac{1}{T_s - T_0}\right)^{1.87}$$

  In the second method, the temperature differential is maintained constant by a control circuit which regulates the heater's voltage *e. In the latter case, e is the output signal.*

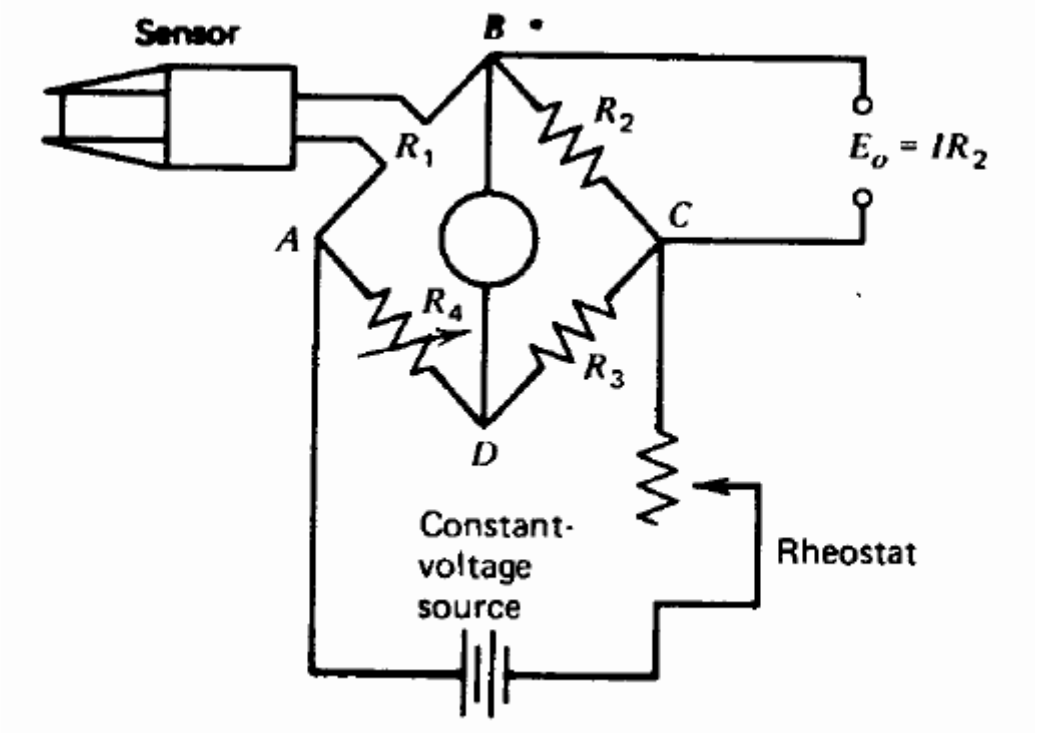
Constant-Current Anemometer Circuit



Constant-Current Anemometer Circuit

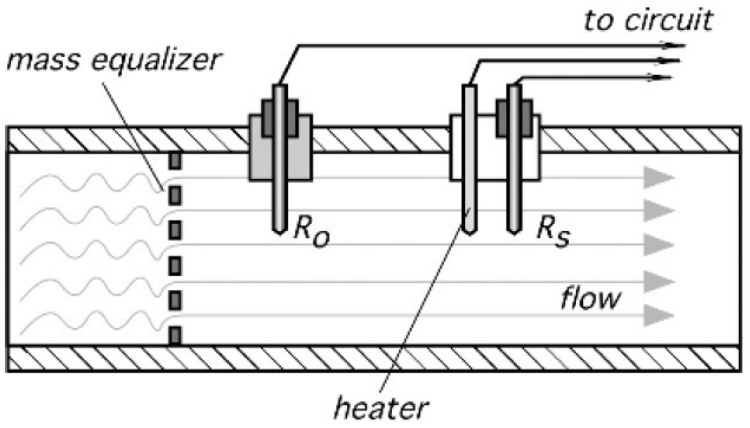


Constant-Voltage Anemometer Circuit



Three-Part Thermo-anemometer

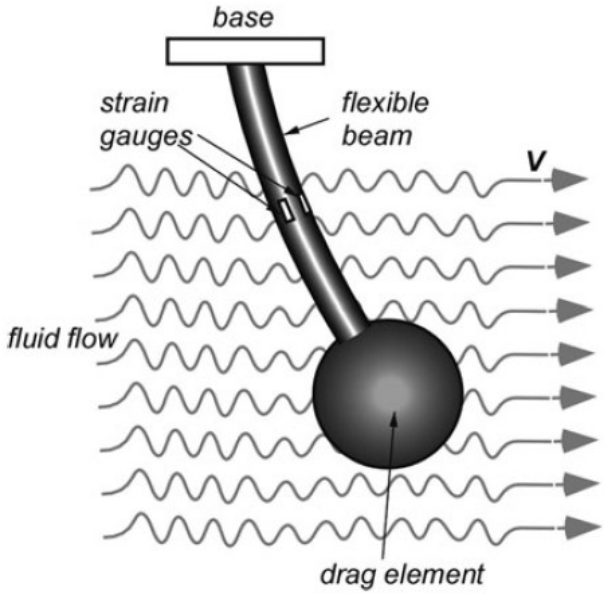
- While designing thermal flow sensors, it is important to assure that the medium moves through the detectors without turbulence in a non-laminar well-mixed flow.
- The sensor is often supplied with mixing grids or tur which sometimes *equalizers*



Three-Part Thermo-anemometer

- Thermal transport flow meters are far more sensitive than other types and have a broad dynamic range.
- They can be employed to measure very minute gas or liquid displacements as well as fast and strong currents.
- Major advantages of these sensors are the absence of moving components and an ability to measure very low flow rates.
- If a small-diameter tubing is required, as in automotive, aeronautic, medical, and biological applications, sensors with moving components become mechanically impractical.

Dynamic Wind Vector Indicator (using Drag Force)

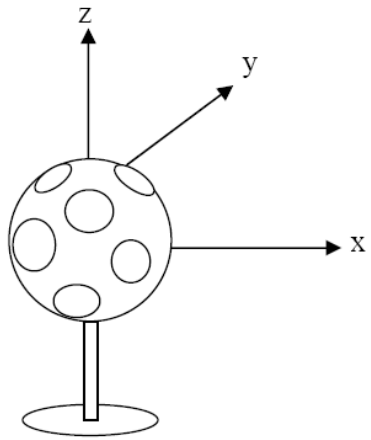


- Wind-vector indicator measures the magnitude and direction of flow velocity in terms of the drag force, F_d ,exerted on a hollow sphere.

$$F_d = C_d \frac{A\rho V^2}{2} \qquad (6.1.4\text{-}1)$$

where C_d = drag coefficient of body, A = projected area of body, ρ = density, and V = flow velocity.

Q.2 A 3-axis forces sensor is used to determine force along x, y, and z direction of a wind-vector indicator. When wind flows with velocity of 60 m/s in x direction, forces reading displays 10 N, 0 N, and 0 N along x, y, and z axis respectively. Determine magnitude and direction of wind when forces reading displays 5 N, 8 N, and –2 N along x, y, and z axis. Assume wind mass density is constant. (6)



Solution

$\because$ $$F_d = \frac{1}{2} C_d A \rho V^2 \quad (1)$$

$\therefore$ $$\frac{F_{d1}}{F_{d2}} = \frac{V_1^2}{V_2^2} \quad (2)$$

$$\frac{10}{\sqrt{5^2 + 8^2 + 2^2}} = \frac{60^2}{V_2^2} \quad (3)$$

$$V_2 = 58.92 \text{ m/s} \quad (4)$$

$$V_2 = 58.92\left(\frac{5}{\sqrt{5^2 + 8^2 + 2^2}} i + \frac{8}{\sqrt{5^2 + 8^2 + 2^2}} j - \frac{2}{\sqrt{5^2 + 8^2 + 2^2}} k\right) \quad (5)$$

$$V_2 = 58.92(0.518 i + 0.830 j - 0.207 k) \quad (6)$$

Pressure Gradient Technique

- A fundamental equation in fluid mechanics is *Bernoulli equation which is strictly* applicable only to steady flow of non-viscous, incompressible medium

$$p + \rho\left(\frac{1}{2}v_a^2 + gy\right) = \text{const}$$

where *p is the pressure ir*
y is the height of the medium's displacement.

- *Bernoulli's equation* allows us to find fluid velocity by measuring pressures along the flow.

Bernoulli equation

$$\frac{P_A}{\gamma_A} + \frac{V_A^2}{2g} + Z_A = \frac{P_B}{\gamma_B} + \frac{V_B^2}{2g} + Z_B \qquad (7.6)$$

where P_A and P_B = absolute static pressures at points A and B, respectively
γ_A and γ_B = specific weights
V_A and V_B = average fluid velocities
g = acc of gravity
Z_A and Z_B = elevations above a given reference level, i.e., $Z_A - Z_B$ is the head of fluid.

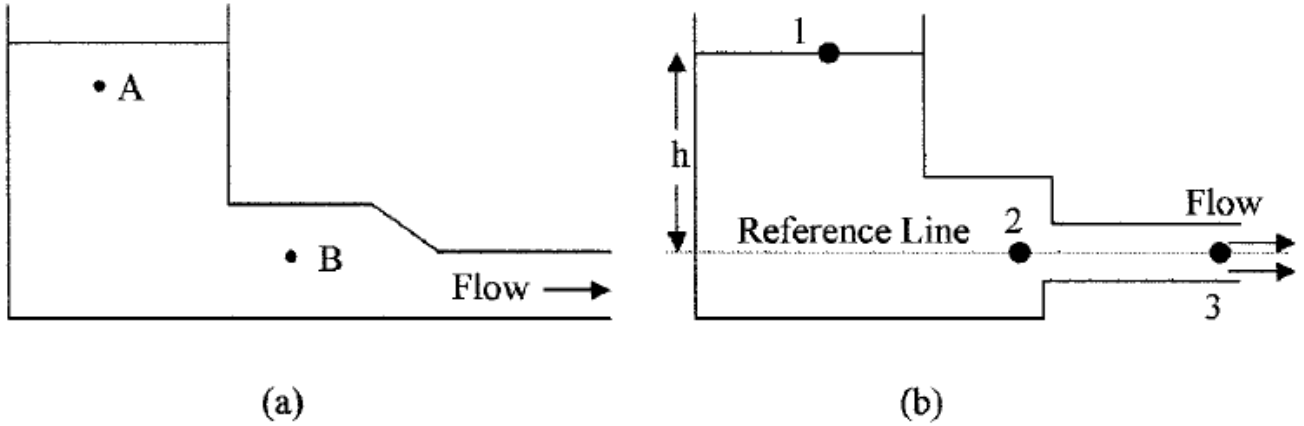


Figure 7.3 Container diagrams (*a*) the pressures at points *A* and *B* are related by the Bernoulli equation and (*b*) application of the Bernoulli in Example 7.3.

Bernoulli equation

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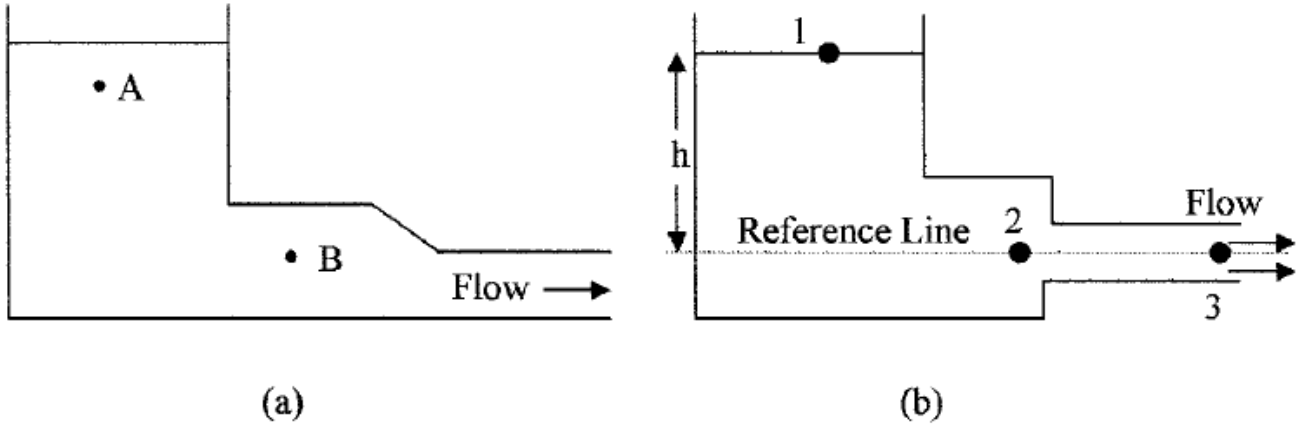

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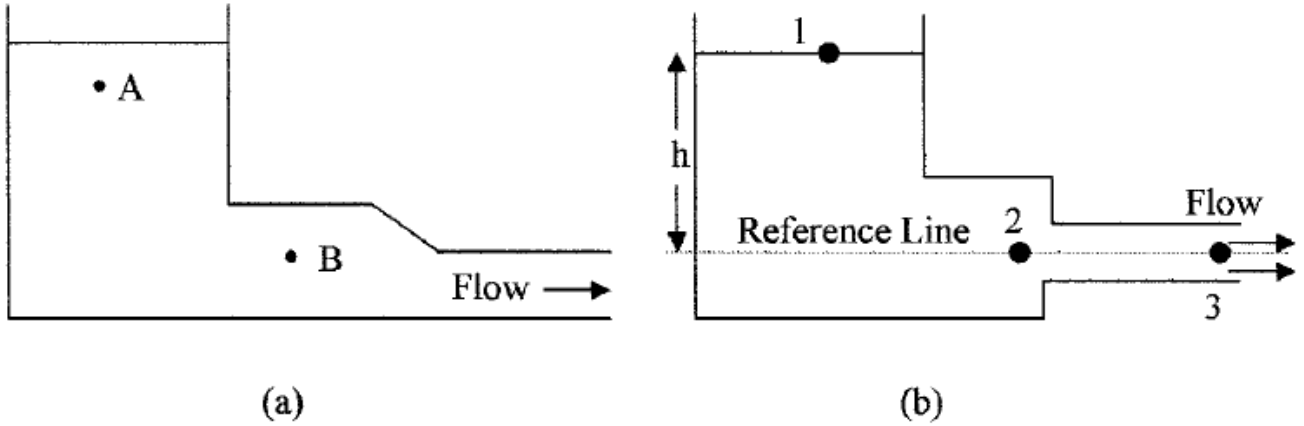

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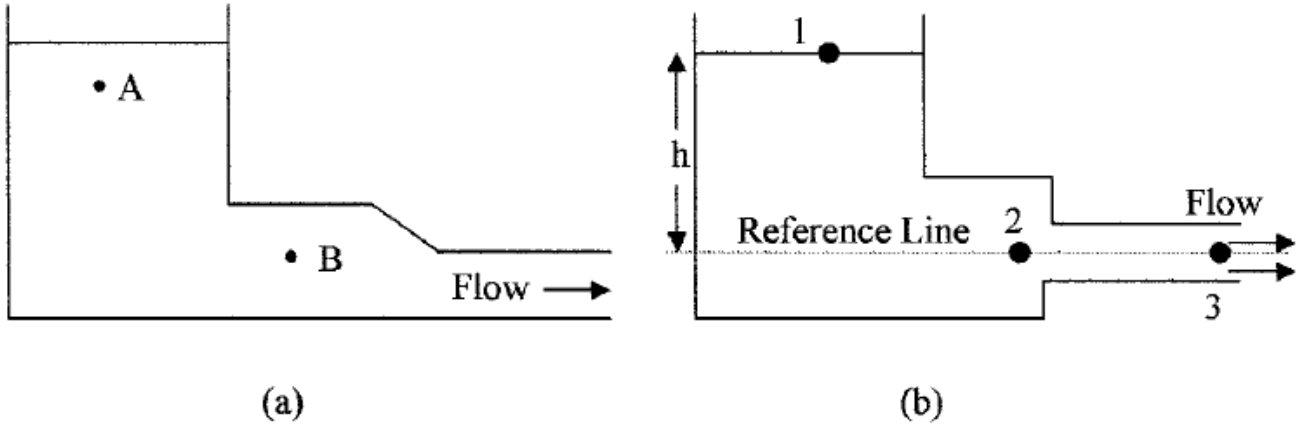

Figure 7.3 Container diagrams (*a*) the pressures at points *A* and *B* are related by the Bernoulli equation and (*b*) application of the Bernoulli in Example 7.3.

The units in Eq. (7.6) are consistent and reduce to units of length (feet in the English system and meter in the SI system of units) as follows:

$$\text{Pressure energy} = \frac{p}{\gamma} = \frac{\text{lb/ft}^2(\text{N/m}^2)}{\text{lb/ft}^3(\text{N/m}^3)} = \text{ft(m)}$$

$$\text{Kinetic energy} = \frac{V^2}{g} = \frac{(\text{ft/s})^2(\text{m/s})^2}{\text{ft/s}^2(\text{m/s}^2)} = \text{ft(m)}$$

$$\text{Potential energy} = Z = \text{ft(m)}$$

In the fluid system shown in Fig. 7.3*b* the flow velocity V at point 3 can be derived from Eq. (7.6) and is as follows using point 2 as the reference line.

$$\frac{P_1}{\gamma_1} + 0 + h = \frac{P_3}{\gamma_3} + \frac{V_3^2}{2g} + 0$$

$$V_3 = \sqrt{(2\ gh)} \tag{7.7}$$

Point 3 at the exit has dynamic pressure but no static pressure above 1 atm, and hence, $P_3 = P_1 = 1$ atm and $\gamma_1 = \gamma_3$. This shows that the velocity of the liquid flowing out of the system is directly proportional to the square root of the height of the liquid above the reference point.

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Example 7.3 If h in Fig. 7.3b is 7.5 m, what is the pressure at P_2? Assume the areas at points 2 and 3 are 0.48 m^2 and 0.3 m^2 respectively.

$$V_3 = \sqrt{(2 \times 9.8 \times 7.5)} = 12.12 \text{ m/s}$$

Considering points 2 and 3 with the use of Eq. (7.6)

$$\frac{P_2}{9.8 \text{ kN}} + \frac{V_2^2}{2 \times 9.8} + 0 = \frac{101.3 \text{ kPa}}{9.8 \text{ kN}} + \frac{V_3^2}{2 \times 9.8} + 0 \qquad (7.8)$$

Using the continuity Eq. (7.3) and knowing that the areas at point 2 and 3 are 0.48 m^2 and 0.3 m^2, respectively, the velocity at point 2 is given by-

$$V_2 = \left(\frac{A_3}{A_2}\right) V_3 = \left(\frac{0.3}{0.48}\right) 12.12 \text{ m/s} = 7.58 \text{ m/s}$$

Substituting the values obtained for V_2 and V_3 into Eq. (7.8), gives the following:

$$\frac{P_2}{9.8} + \frac{(7.58)^2}{2 \times 9.8} + 0 = \frac{101.3}{9.8} + \frac{(12.12)^2}{2 \times 9.8} + 0$$

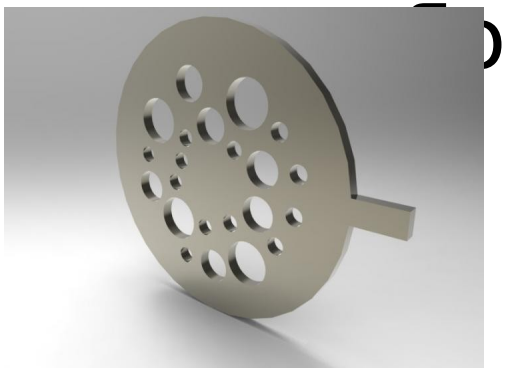
$$P_2 = 146 \text{ kPa(a)} = 44.7 \text{ kPa (g)}$$

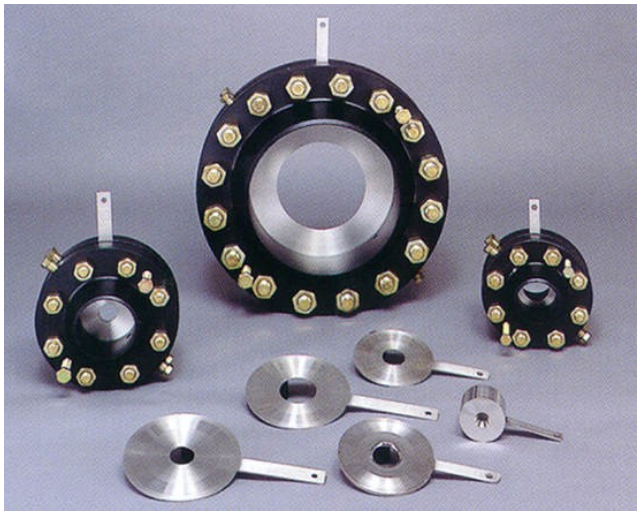
Common Flow Meters

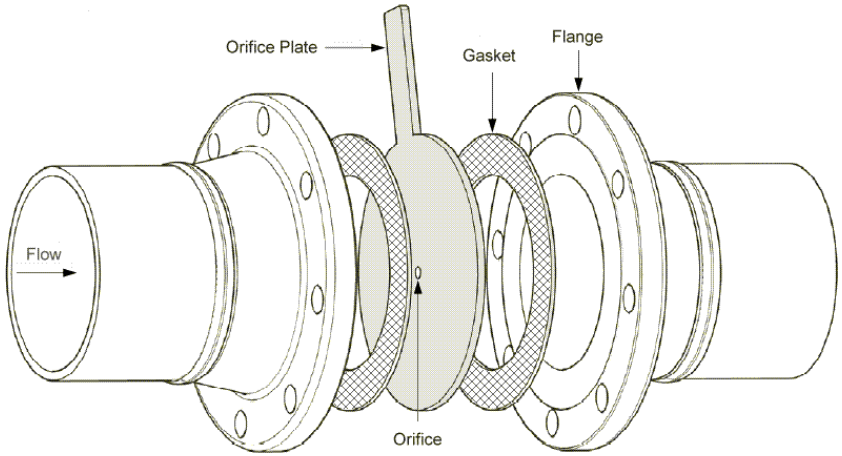
- Orifice meter
- Venturi meter
- Rota meter
- Pitot tube

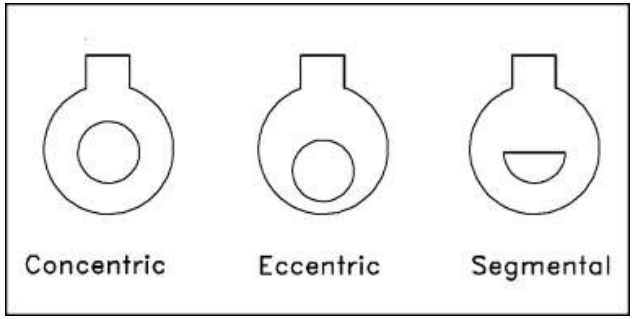
Orifice Plate Based Flow Metering

- An orifice plate is thin plate with a hole in middle which helps to flow rate

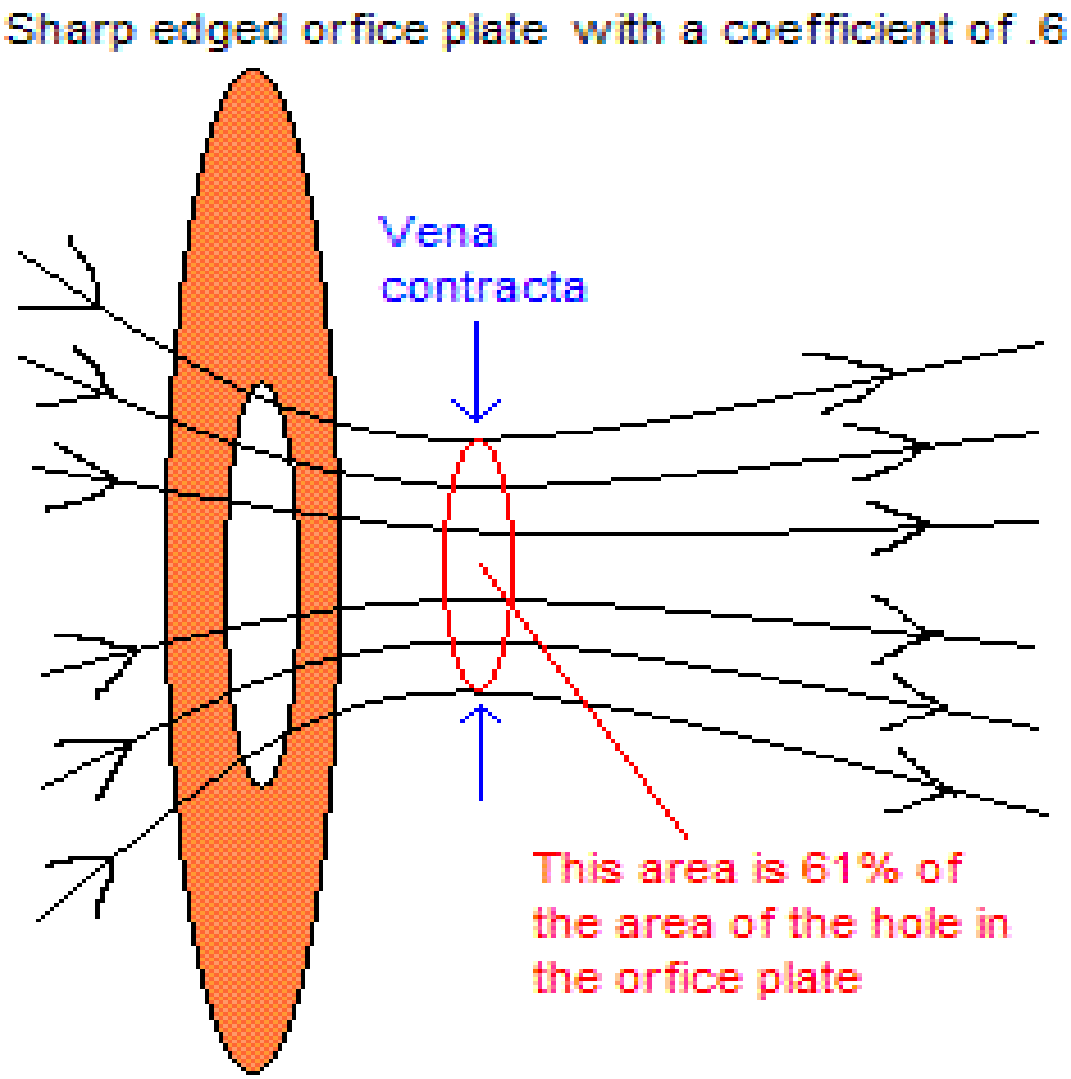








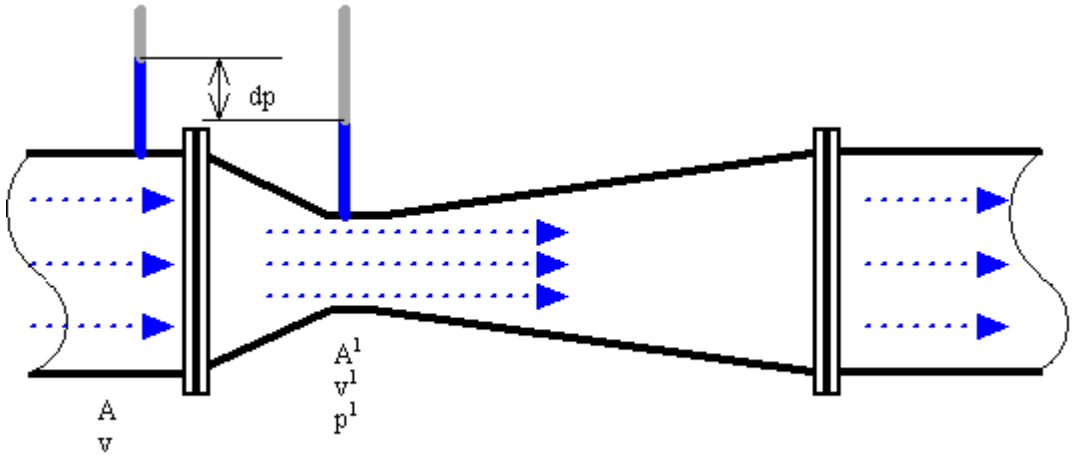
Orifice Plate Based Flow Metering

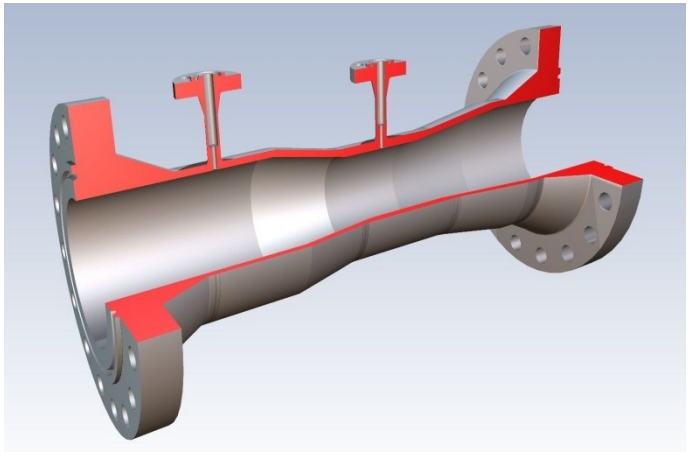

Sharp edged orfice plate with a coefficient of .61
Vena
contracta
This area is 61% of
the area of the hole in
the orfice plate

Vena contracta is the point in a fluid stream where the diameter of the stream is the least, and fluid **velocity** is at its maximum

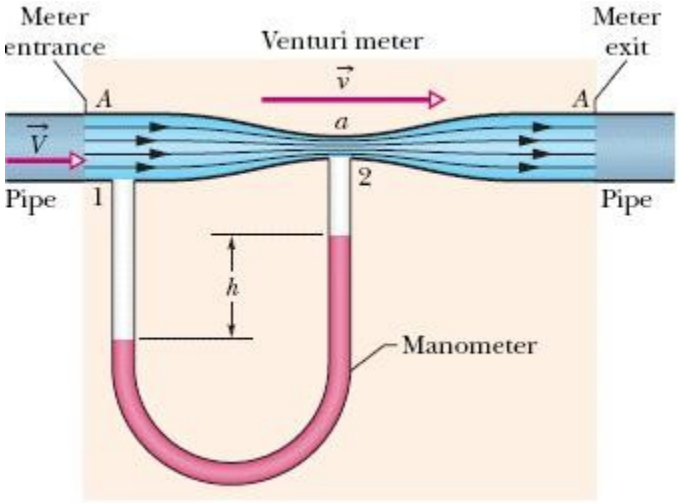
Venturi Meter

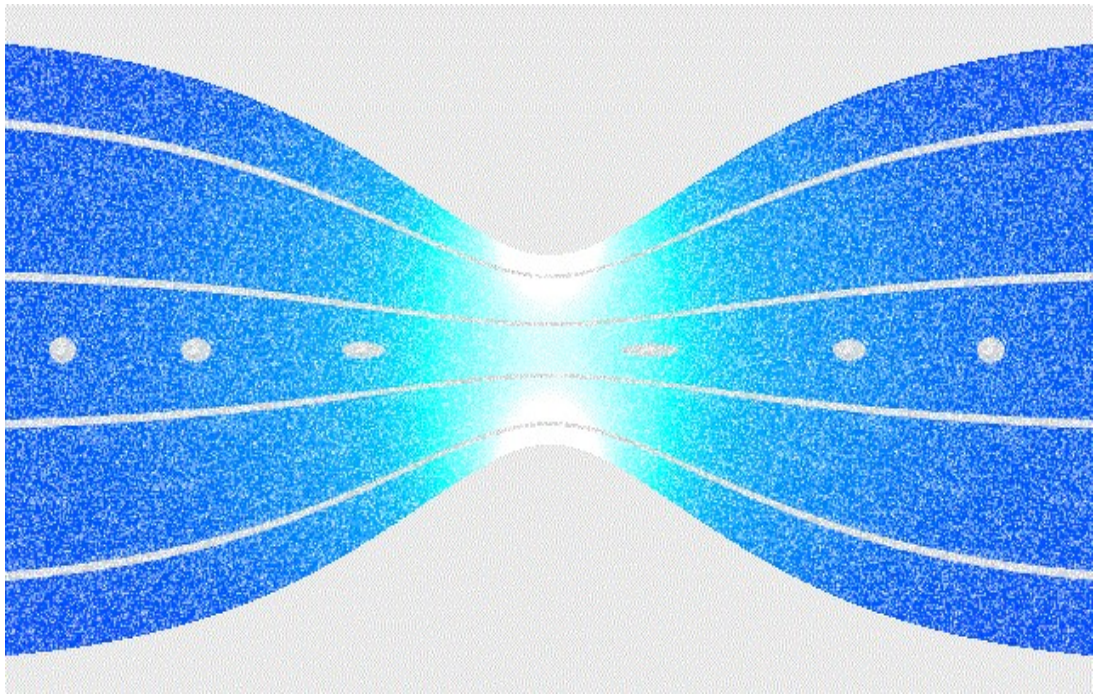
- When fluid passes through converging side its velocity increases maximum at throat and and become same after passing throat



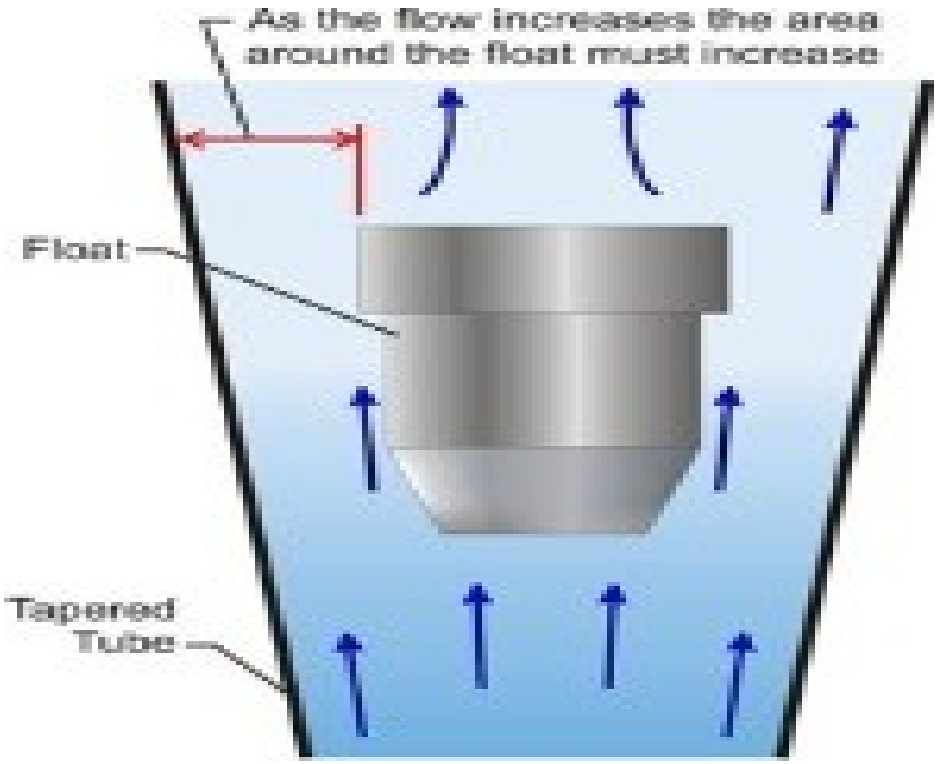


Venturi Meter





Rotameter (Variable Area Flow Meter)



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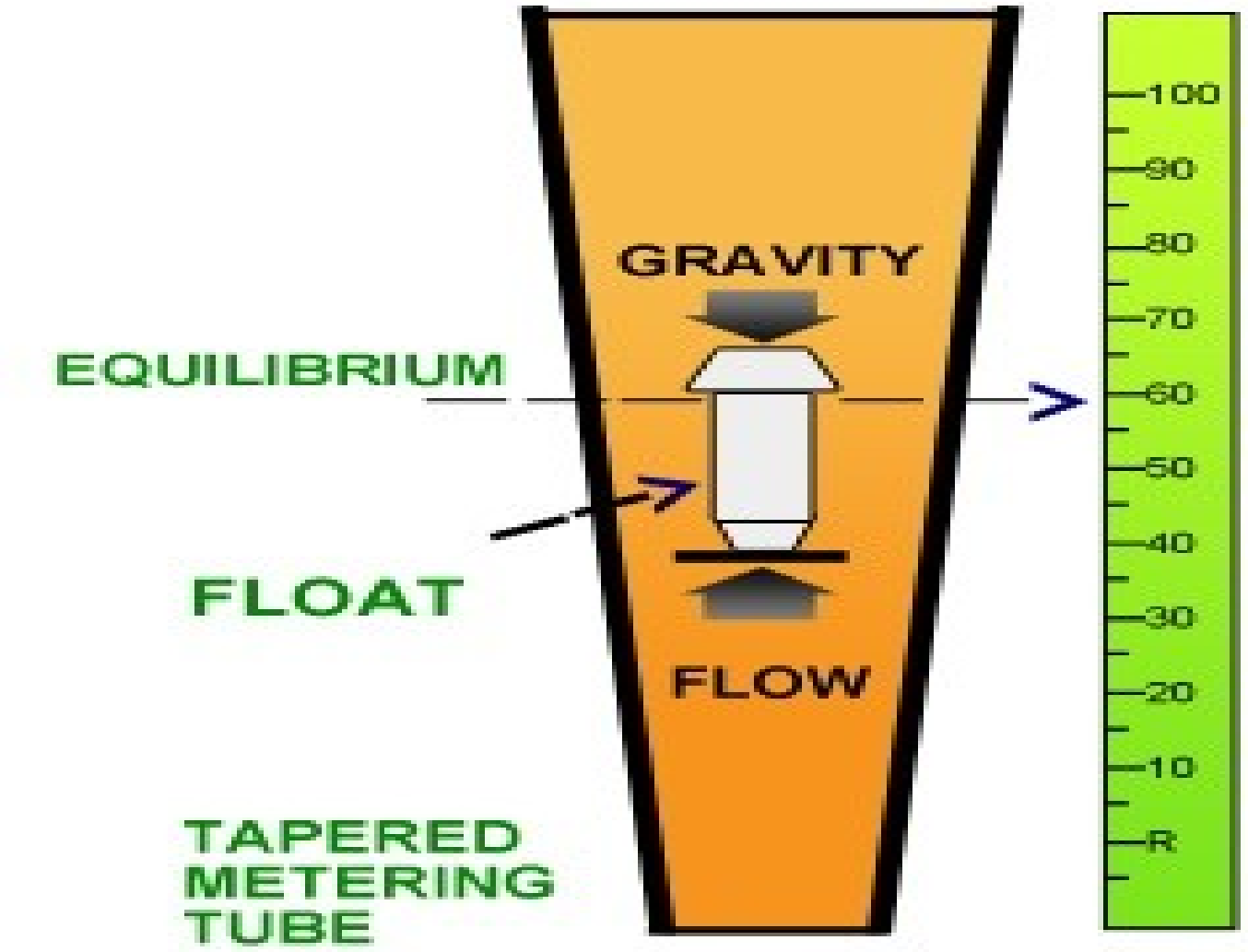


Rotameter (Variable Area Flow Meter)

Rotameter: Advantages

- A rotameter requires no external power or fuel, it uses only the inherent properties of the fluid, along with gravity, to measure flow rate.
- A rotameter is also a relatively simple device that can be mass manufactured out of cheap materials, allowing for its widespread use.
- Since the area of the flow passage increases as the float moves up the tube, the scale is approximately linear.
- Clear glass is used which is highly resistant to thermal shock and chemical action.

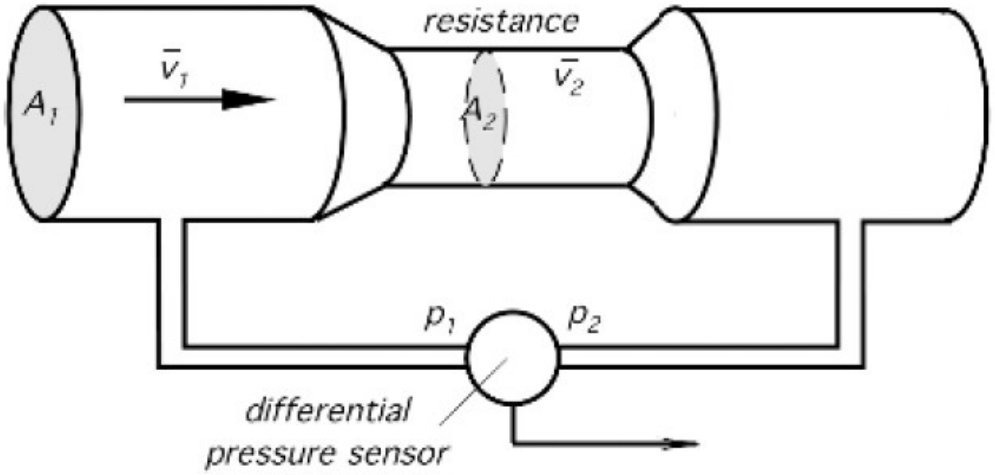
Rotameter: Disadvantages

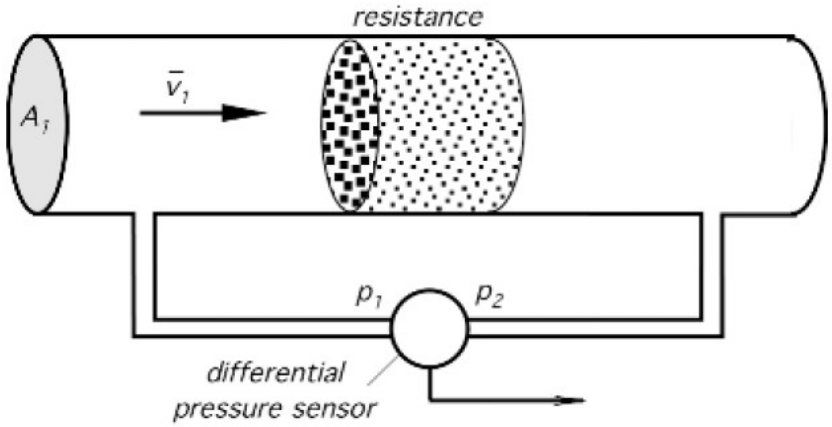
- Due to its use of gravity, a rotameter must always be vertically oriented and right way up, with the fluid flowing upward
- Due to its reliance on the ability of the fluid or gas to displace the float, graduations on a given rotameter will only be accurate for a given substance at a given temperature.
- The main property of importance is the density of the fluid; however, viscosity may also be significant.
- Floats are ideally designed to be insensitive to viscosity; however, this is seldom verifiable from manufacturers' specifications.
- Either separate rotameters for different densities and viscosities may be used, or multiple scales on the same rotameter can be used.

Rotameter: Disadvantages

- Due to the direct flow indication the resolution is relatively poor compared to other measurement principles.
- Readout uncertainty gets worse near the bottom of the scale.
- Since the float must be read through the flowing medium, some fluids may obscure the reading.

Pressure Gradient Technique





Course/Course Code:

Data Acquisition and Microcontroller (MC-546)

Lecture # 02

NED University of Engineering & Technology

SENSORS AND TRANSDUCERS

Audio by

Engineer R Hasan

*Student of **Masters** in Mechanical from **NED University** of Engineering and*

Course/Course Code:

Data Acquisition and Microcontroller (MC-546)

Lecture # 04

NED University of Engineering &

SIGNAL CONDITIONING

Audio by

Engineer R Hasan

*Student of **Masters** in Mechanical from **NED University** of Engineering and Technology, Pakistan.*

Pressure Gradient Technique

- A differential pressure sensor is positioned across the resistor. When moving mass enters the higher-resistance area, its velocity increases in proportion $v_{1a} = v_{2a} R$e resistance increase

$$\Delta p = p_1 - p_2 = \frac{\rho}{2}(v_{2a}^2 - v_{1a}^2) = k\frac{\rho}{2}v_{2a}^2(1 - R^2)$$

$$v_{2a} = \frac{1}{\sqrt{k(1 - R^2)}}\sqrt{\frac{2}{\rho}\Delta p}.$$

Pressure Gradient Technique

$$q = \xi A_2 \sqrt{\Delta p}$$

where ξ is a coefficient which is determined through calibration

- An advantage of the pressure gradient method is in the absence of moving components and use of standard pressure sensors which are readily available.
- A disadvantage is in the restriction of flow by resistive devices

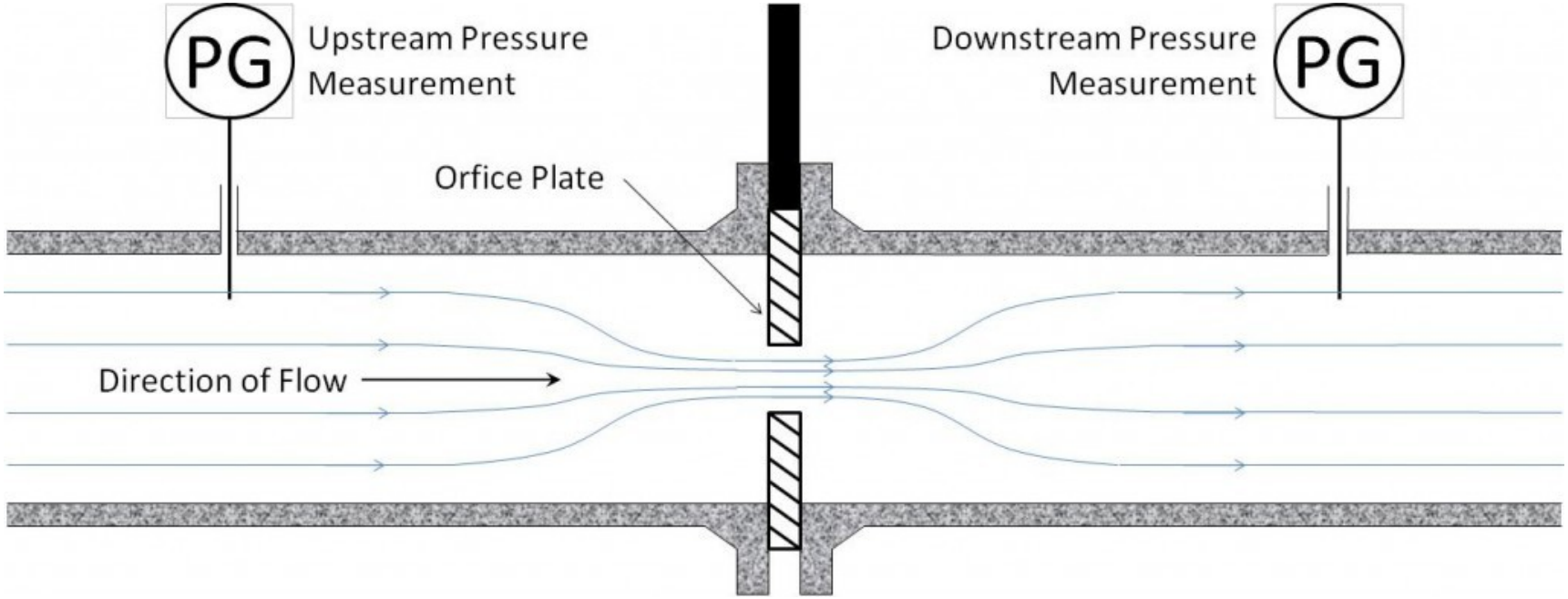
Differential Pressure Measurement

- Differential pressure measurement sensor technologies can be used for both airflow and liquid flow measurements
- Principle:
  - Pressure drop across the meter is proportional to the square of the flow rate and
  - Flow rate is found by measuring the pressure differential and taking the square root

Differential Pressure Measurement

- Primary and secondary element
- Primary element causes a change in the kinetic energy, to create the differential pressure in the pipe.
  - The unit must be correctly matched to the pipe size, flow conditions, and the properties of the liquid being measured
- Secondary element measures the differential pressure and outputs the signal that is converted to the actual flow value.

Differential Pressure Measurement

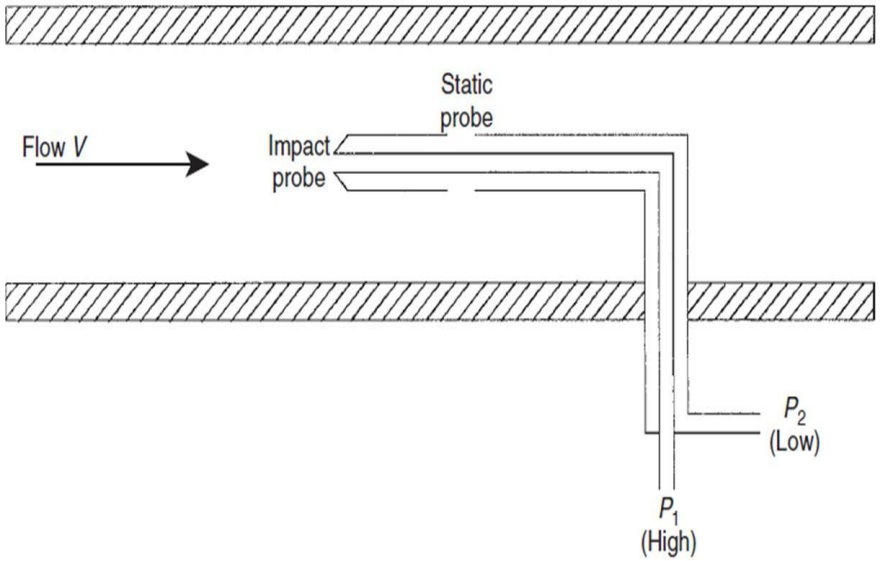


Differential Pressure Measurement

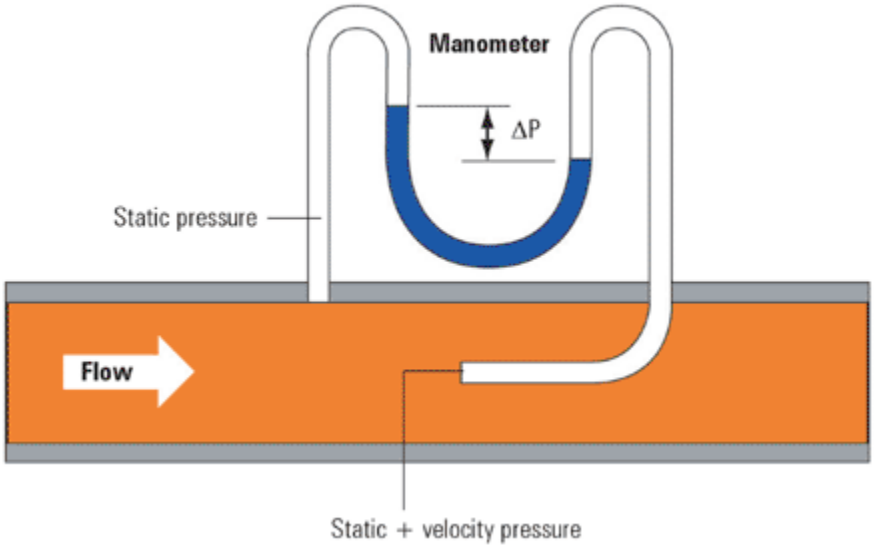
- Common differential pressure flow devices include Pitot tubes and numerous other types of velocity pressure-sensing tubes, grids, and arrays.
- Pitot tube consists of two tubes that measure pressure at different locations within a pipe.
  - One tube measures static pressure, usually at the pipe wall, and
  - the other measures impact pressure (static pressure plus velocity head).

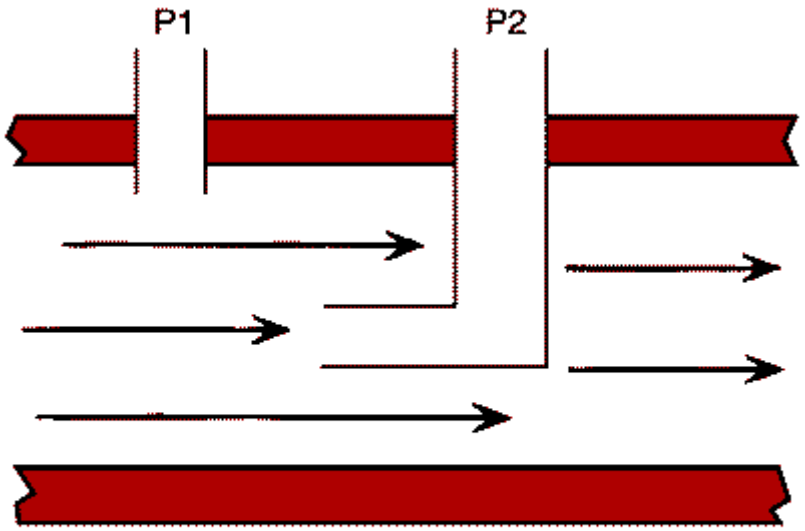
Pitot Tube Meter

- When Pitot tube placed in a pipe from which fluid is flowing as pitot tube has two tubes one with large diameter having holes which measure static pressure . while fluid entering small tube on striking become rest kinetic energy converted into pressure energy exerted a pressure called impact pressure the difference in total pressure minus static pressure give pressure difference which give velocity of fluid by Bernoulli's equa



Pitot Tube Arrangement





$Q^2 \alpha (P_2 - P_1)$

$Q \alpha \sqrt{(P_2 - P_1)}$

Differential Pressure Measurement

- The faster the flow rate, the larger the impact pressure.
- Pitot tubes are low-cost devices
- Prone to clogging
- Only measure flow at a single point and need to be installed at the point of maximum flow
- Changes in velocity profile can cause major errors
- Averaging Pitot tubes have several ports for measuring flow at multiple locations makes it possible to take changing velocity profiles into account

Differential Pressure Measurement

- To measure
  - water flow,
  - differential pressure flow devices typically either measure velocity pressure (insertion tube type), or measure the drop in pressure across a known restriction.
    - Orifice plates, flow nozzles, Venturis, and Pitot tubes are types of restrictions commonly used